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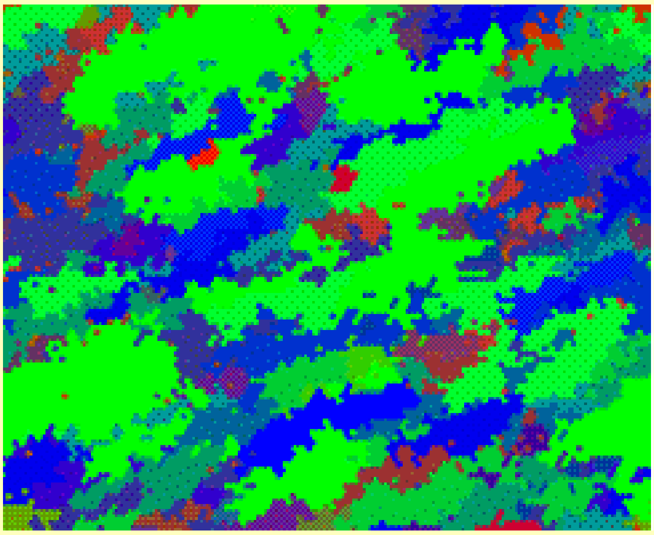
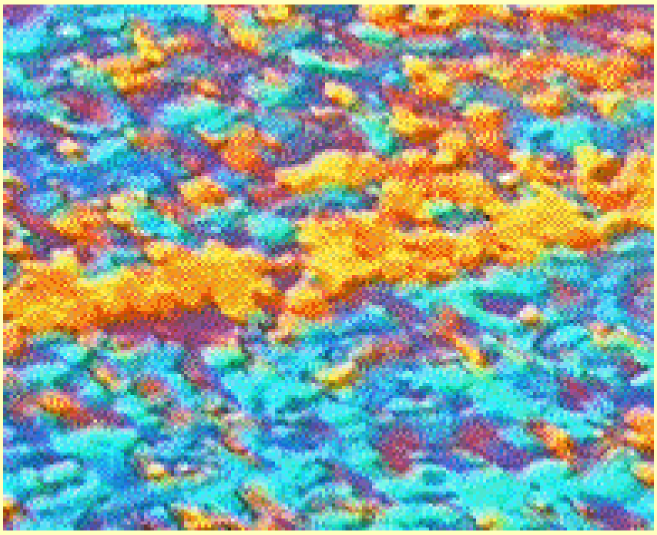
VIEPS/Mainz Deformation Microstructures Course





This page contains the links to all the course related information available for the 2000 VIEPS/Mainz short course presented by Mark Jessell at the Department of Earth Sciences, Monash University, Australia & Paul Bons at Institut für Geowissenschaften - Tektonophysik, Johannes Gutenberg Universität Mainz, Germany. Many of the pictures used in Lectures 1 & 2 of this course were graciously donated by Patrice Rey, the dislocation movie comes from Renée Heilbronner, the TEM dislocation pictures come from Alice Post, and the analogue movies are courtesy of Youngdo Park, Jin-Han Ree, Win Means, & Coen ten Brink. Each year the course gets modified, and the web address of the current version of this site is http://www.earth.monash.edu.au/Teaching/mscourse/

Lecture Notes

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- Lecture 2 Recrystallisation and Recovery
- Lecture 3 Grain Shape and Crystallographic Preferred Orientations
- Lecture 4 Shear Zones, Porphyroclasts & Porphyroclasts a b
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- Lab 2 Recrystallisation and Recovery a b c
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- Lab 4 Shear Zones, Porphyroblasts & Porphyroclasts a b
- Lab 5 Veins and Vein Growth a b

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Questions

You can email questions about this course to Mark Jessell or Paul Bons

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Viewing the movies in these course notes

There are many animations and movies strewn through these course notes, all in QuickTime or animated gif formats. This means your browser must be capable of viewing the movies, either in situ or in separate windows. All movies are surrounded by a blue frame

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Who is this course for, and how should it be used?

This course is aimed at a first year graduate level or a senior undergraduate level, but it really depends how much geology, structural geology and materials science you have already done.

Anyone that wants to make use of any or all of this course is free to do so in any non-commercial way they like. You will find that the written explanation of many pictures is very limited, which means either you need to use this course in conjunction with a real live lecturer, or go and buy a good book, or preferably both. We use the course as the basis for our lectures, and in fact we started building a web based course simply because it was a good way of cataloguing all the pictures and movies we wanted to show our students.

For the labs, we provide pictures of thin sections, however the real things are much more informative.

Lecture 1- Microstructures and Deformation Mechanisms

VIEPS/Mainz Microstructure Course

1) Introduction

We can define microstructures (based in part on a Hobbs, Means & Williams 1976 definition) to be:

> *"the small-scale arrangement of geometric and mineralogical elements within a rock."*

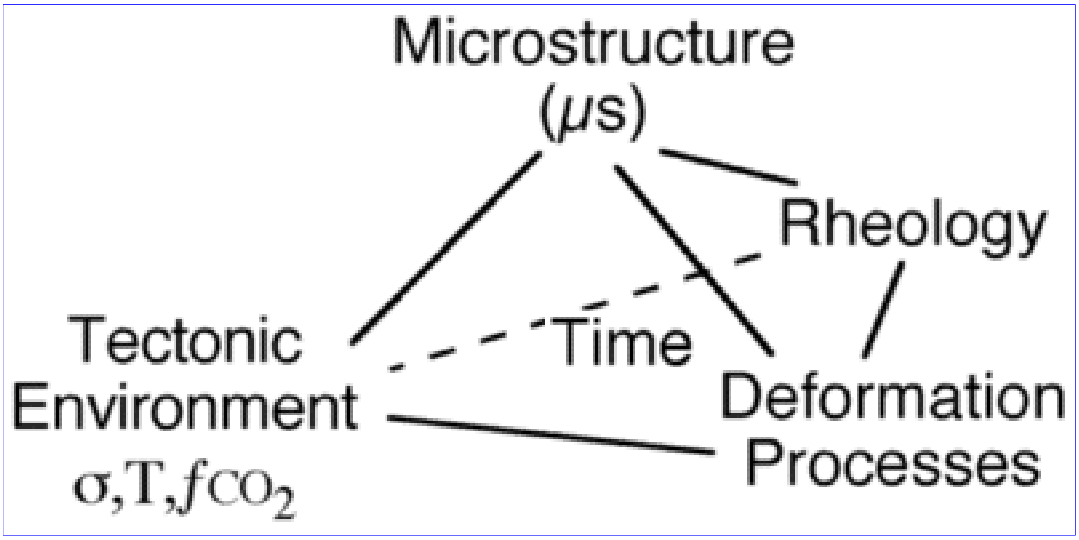
This of course begs the question as to what small-scale means, and we will be going on a tour of microstructures in this course at increasing scales:

Atomic scale (eg defects) ->
intra-crystalline (eg twinning) ->
inter-crystalline (eg porphyroblasts) ->
multi-grain interactions (eg shear bands, continuum mechanics)

Microstructures are also called *fabrics* by some people, or *microfabrics*.

2) Why do we study microstructures?

- To establish the link between process, environment & microstructure via general constitutive equation eg Dorn 1957
- The (Micro)structure is a function of the competing processes in a rock: (PROCESS RATE=DRIVING FORCE*KINETICS) as they act on an initial (Micro)structure. By understanding this relationship we can interpret microstructures in terms of the history of temperature (**T**) , pressure (σ), the CO2 fluid pressure (fCO_2) and other boundary conditions that control both the driving force and the kinetics



- To provide evidence of deformation processes, which in turn provides:
  - evidence of rheology during deformation, which is important for geodynamic interpretation
  - interpretation of deformation history
  - evidence of metamorphic environment
- interpretation of seismic anisotropy
- microstructural geochemistry

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3) How do we study microstructures

- Field work
  - measurement of cleavages & lineations, etc (Hobbs, Means & Williams 1976)
    measurement of numerous types of sense of shear (aka kinematic) indicators Passchier, C.W. & Trouw, R.A.J. 1996.
- Lab analysis
  - Observation
    - microscopy - optical thin section analysis
    - SEM - Scanning Electron Microscope - observes surfaces only c.f. reflected light microscopy
    - TEM - Transmission Electron Microscope - thin foil samples c.f. transmitted light microscopy
    - Cathodoluminescence (CL)-displays trace chemical variations
  - Quantitative analysis
    - Crystallographic Preferred Orientations (CPO)
    - Grain Shape Foliations (GSF)
    - Grain Size Distributions
    - AVA (mapping crystallographic orientations across a thin section)
    - Stable isotope studies
- Experiments

  -rock mechanics/fabric (Tullis & Tullis 1986)

-info with ceramics, metals, ice: All crystals the same, sort of (Ashby & Brown 1981)
-other crystalline analogues (Means 1989)
-numerical simulation (Jessell & Lister 1990)

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4) Deformation Mechanisms & Processes

a) Definitions: *Deformation Mechanisms are processes that lead to a change in shape of rock*

- There are many types of deformation mechanisms which have been recognised in rocks and other crystalline materials, such as ceramics and metals. We provide a table of deformation mechanisms and processes and the effects they have on microstructure.

There are many other processes, often deformation related, that don't lead to change in shape

- grain boundary migration
- rotation recrystallisation
- metamorphic reaction

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b) Defects- *imperfections in the structure of a crystal, and can be 0-dimensional, 1-dimensional or 2-dimensional*

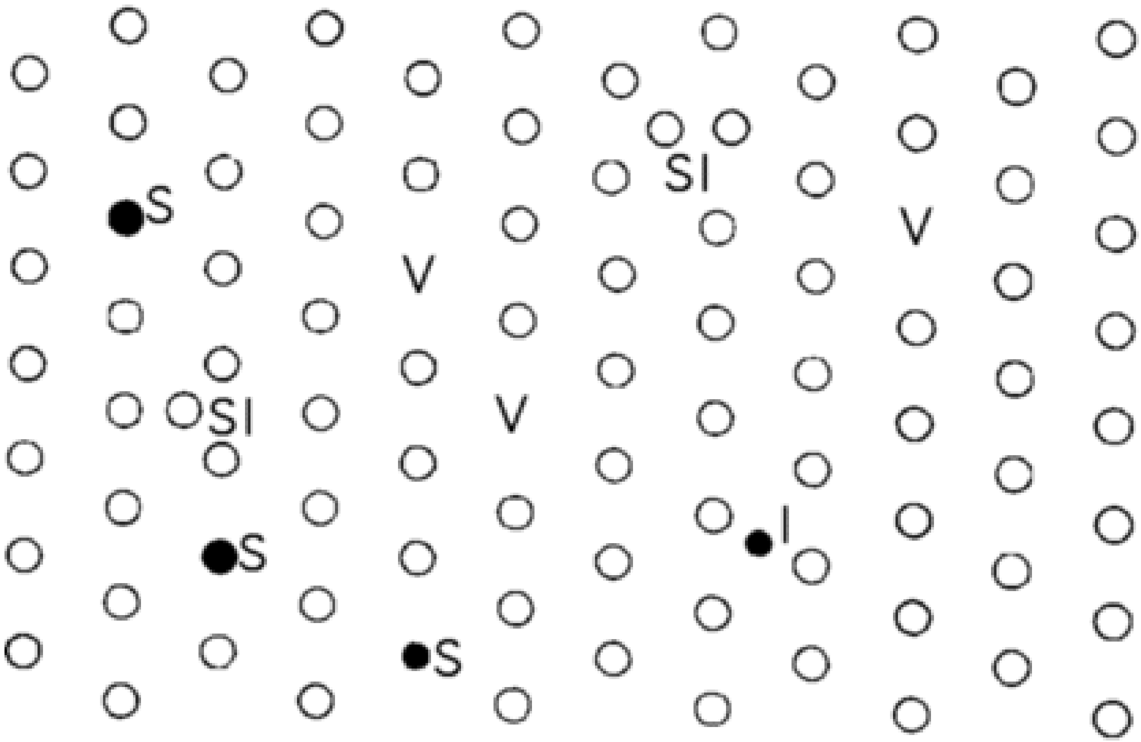
i)Why are defects so important?

- They can speed up the process of crystal growth by orders of magnitude (geometry)
- The distorted crystal lattice around defects provides rapid diffusion pathways within crystals (geometry)
- They are intimately involved in several deformation mechanisms (kinematics)
- Provide a driving force for many deformation processes (dynamics)
- Can weaken the strength of a crystal by several orders of magnitude (dynamics)
- The movement of dislocations can lead to the formation of crystallographic preferred orientations

ii) Defects in crystals:

- **Point** 0-D known as *point defects*
  - vacancies, interstitials, discrete 2nd phase

Point Defects

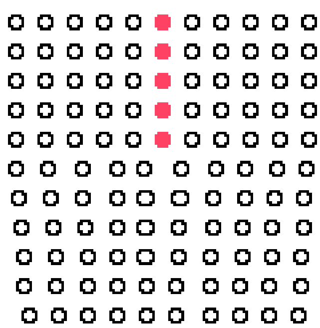


S = substitutional impurities
V = vacancies
I = interstitial impurities
SI = self-interstitials

- **Line**: 1-D known as *dislocations*

Linear defects:

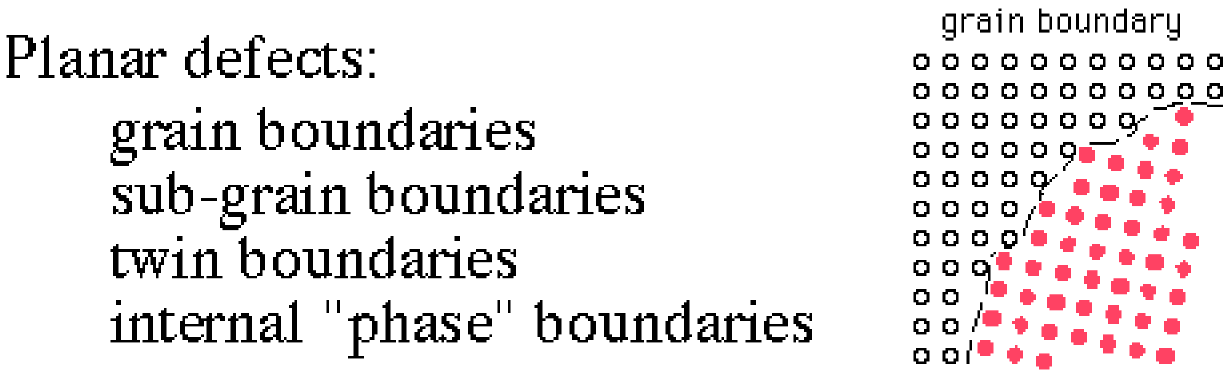
dislocations (screw & edge)



- dislocations are important for their:
  - geometry - each dislocation represents a small angular distortion of the lattice, a lot of them together can result in a curved crystal lattice, or a sharp misorientation across a boundary. Dislocations can also act as fast diffusion pathways.

- kinematics - the movement of dislocations results in the accumulation of deformation within a crystal. The deformation of a material by the movement of dislocations is known as crystalline plasticity
- dynamics - the distortion around a dislocation provides an energy source for other processes such as grain boundary migration.

- **Plane**: 2-D boundaries between different grains or parts of grains
  - grain boundaries, twins, internal phase boundaries, stacking faults
  - Grain boundaries will be discussed in much more detail in Lecture 2.



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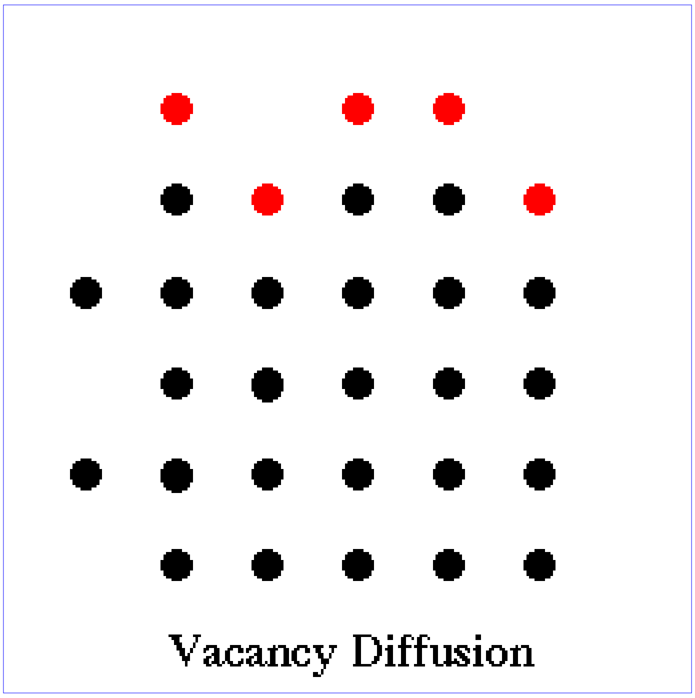
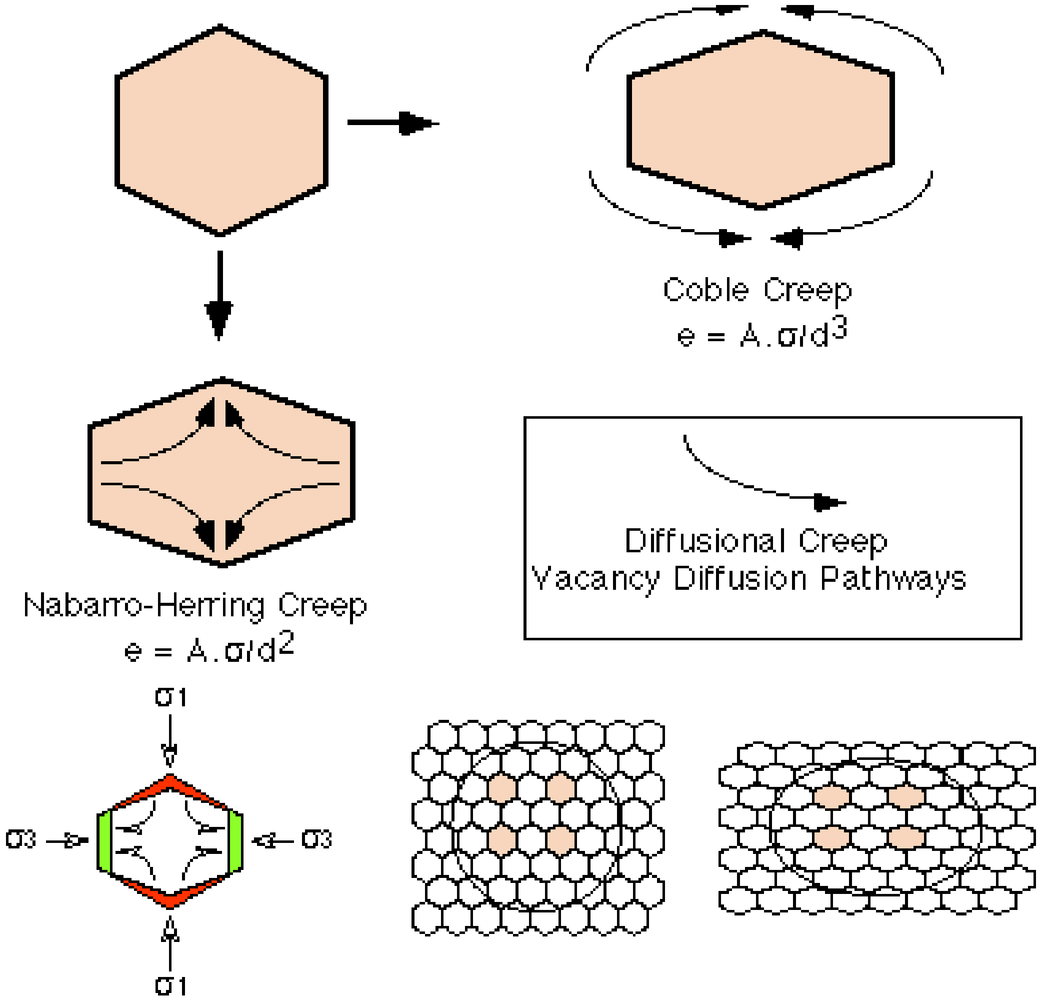
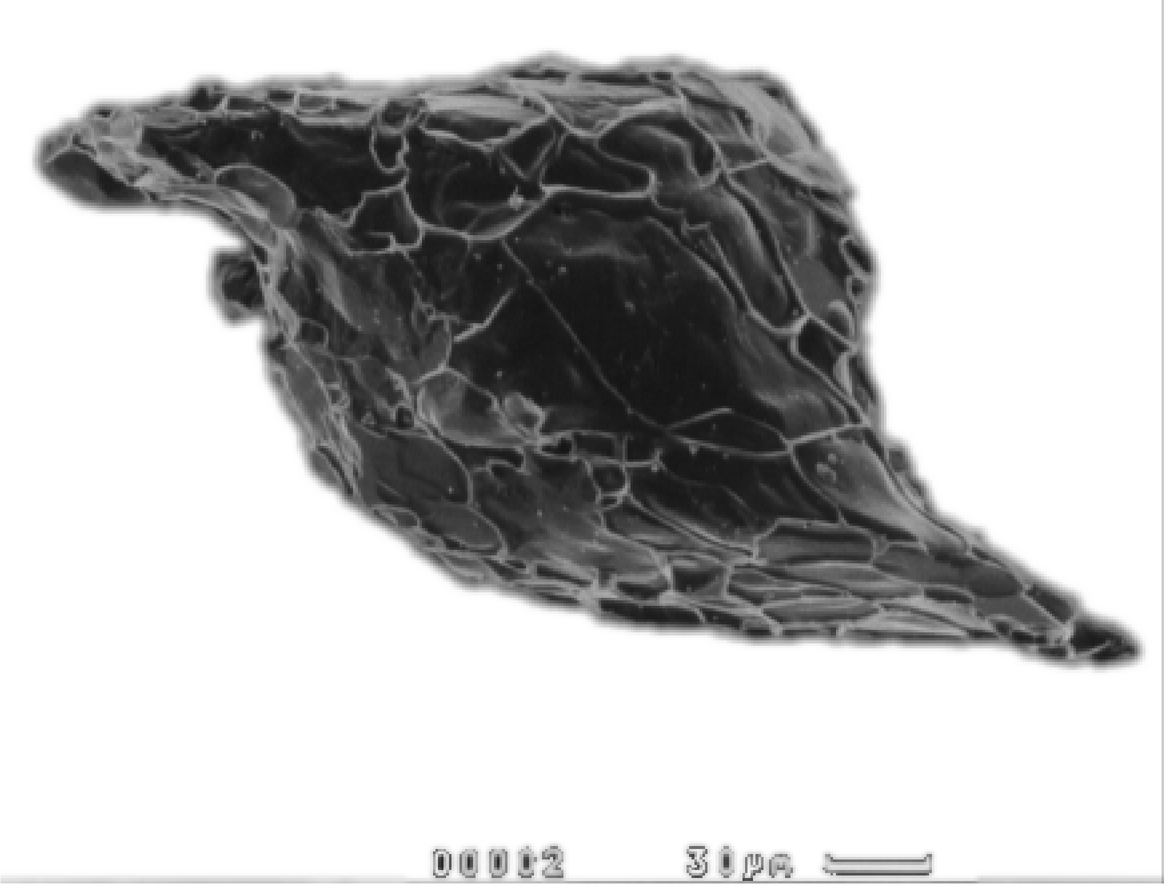
c) Movement of Point Defects: Coble creep & Nabarro-Herring creep:

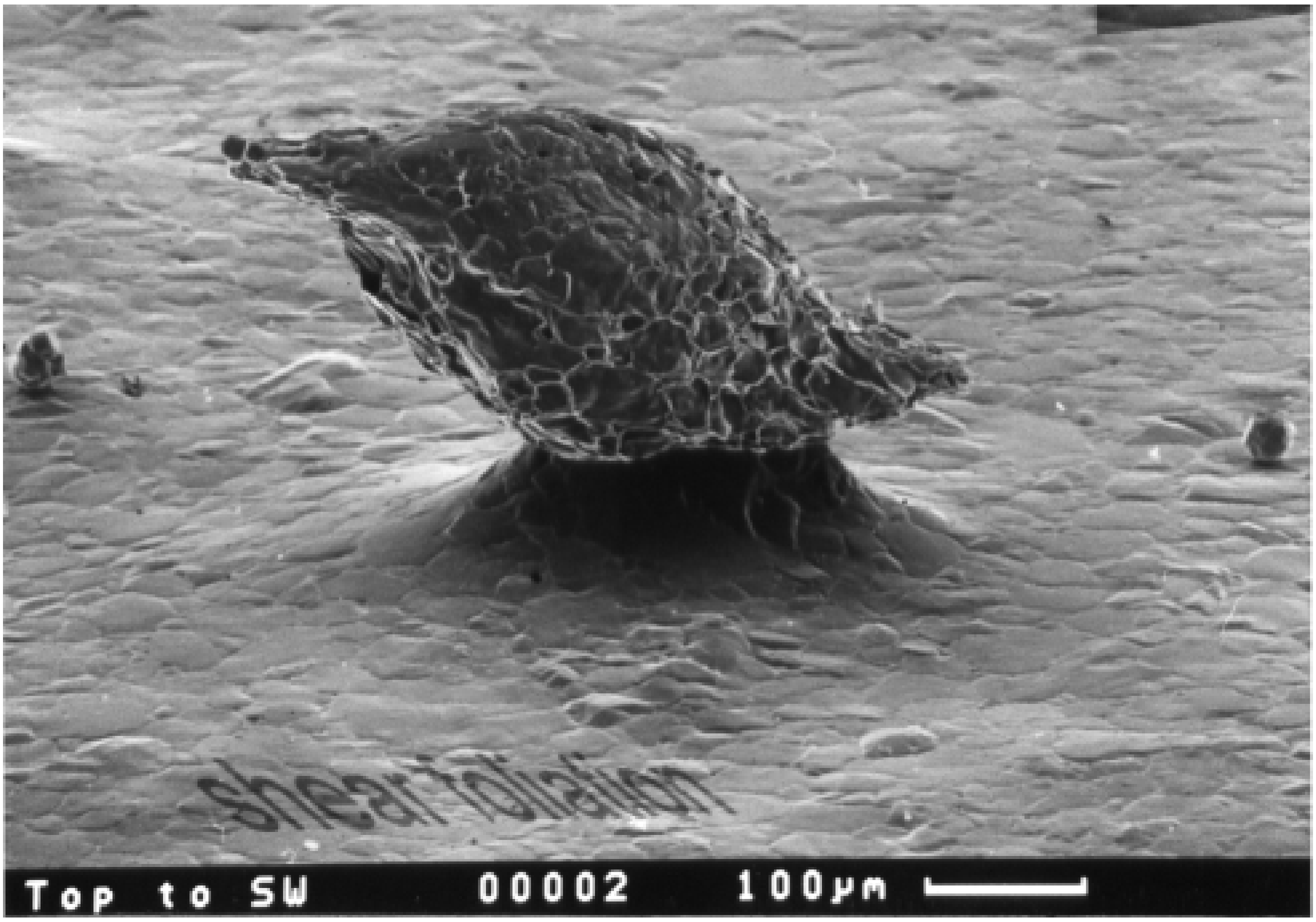
these two processes involve the non-random motion of point defects and can cause a change in shape of a crystal, and are thus deformation mechanisms. The movie just below shows vacancies moving through a crystal, and this is known as Nabarro-Herring Creep. If the vacancies diffuse around the grain margins, it is known as Coble Creep. Click on the picture below to see how vacancy diffusion works.





The images below are of detrital quartz grains in a calcite shear zone. they are single crystals with no evidence of rotation recrystallisation in wings. The lace network on surface reflects cte-cte-qtz triple junctions. They probably formed as a result of Coble and/or Nabarro-Herring creep. Images courtesy of Michel Bestmann (michel@geol.uni-erlangen.de Institut für Geologie und Mineralogie, Schloßgarten 5, 91054 Erlangen, Germany)





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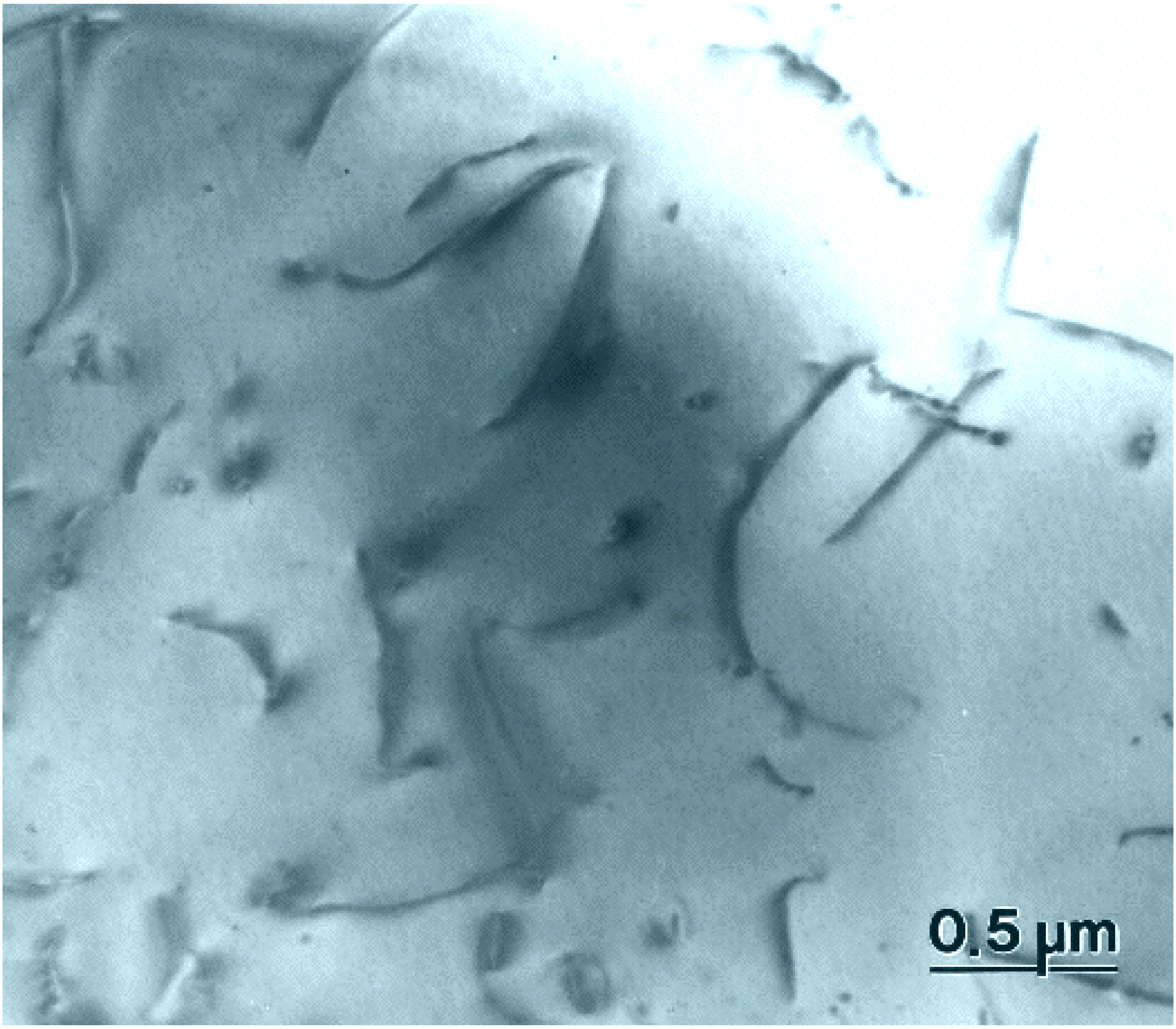
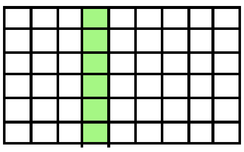
d) Direct Observation of dislocations:

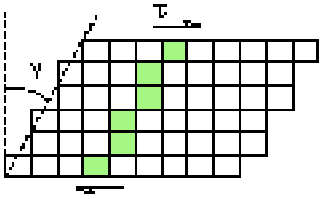
- Etch pits (acids preferentially etch intersection of dislocation with crystal surface)
- Decoration by heat treatment (trace elements precipitate on dislocations)

- Transmission Electron Microscopy (TEM)- a very thin 0.2-3 μ specimen is required i) Bright field image. This TEM image shows the interior of a quartz grain experimentally deformed by Alice Post whilst doing her PhD at Brown University.

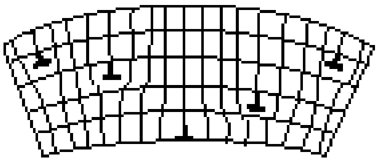


iii) Undulose extinction- demonstrates the effect of large numbers of dislocations producing a curved lattice

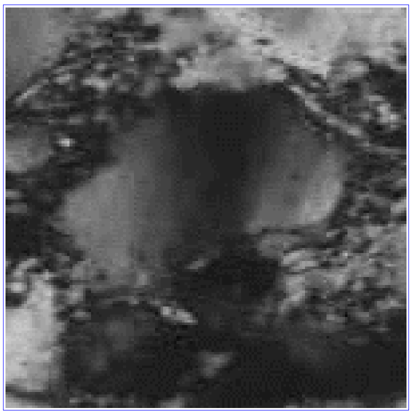




Dislocation gliding



flexure



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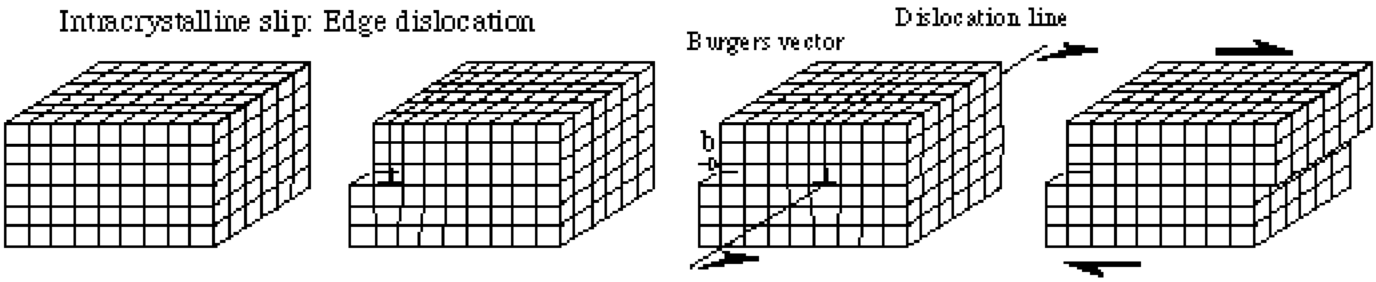
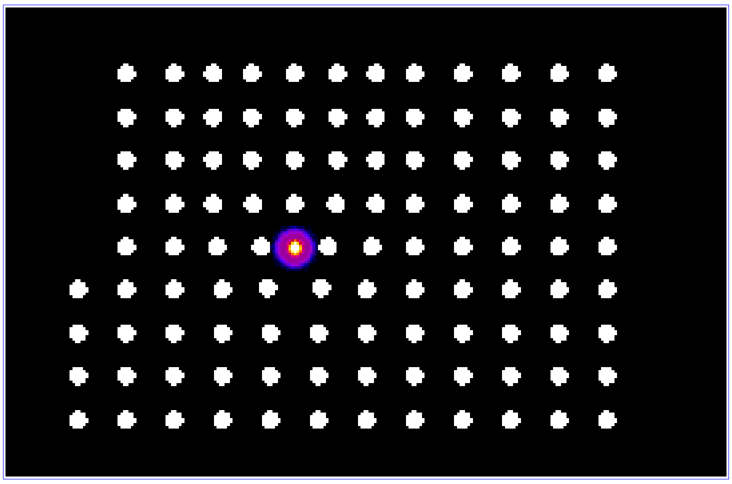
e) Movement of dislocations:

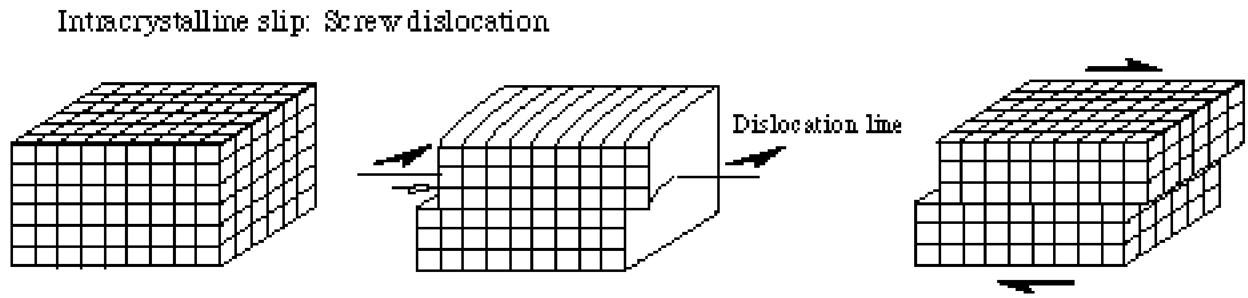
- Slip Systems: any given mineral will favour dislocation motion in particular crystallographically controlled directions. The plane in which the dislocation moves is called the slip plane, and the direction in which it moves is called the slip direction.
- Burgers vector: the length of the dislocation of the crystal lattice caused by a single dislocation is known as the Burgers vector, and this will be constant for any one slip system.
- The Critical Resolved Shear Stress (CRSS) is the stress (as resolved onto the slip plane in the slip direction) needed to cause dislocation motion, ie break shortest bonds. Typically it decreases with increasing temperature for all slips systems in a mineral, however it may not decrease at the same rate for all systems.
- edge dislocation movement results in part of the crystal moving perpendicular to the dislocation line



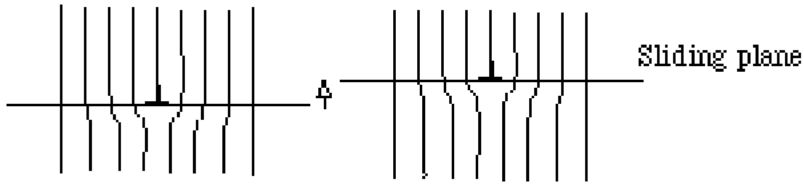


Dislocation glide (edge dislocation)

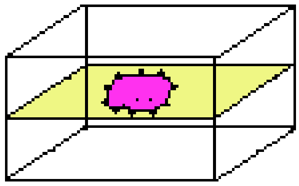
- screw dislocation movement results in part of the crystal moving parallel to the dislocation line



- climb is a diffusive process whereby the dislocation line moves perpendicular to the dislocation line direction, but within the plane of the extra half-plane of atoms.

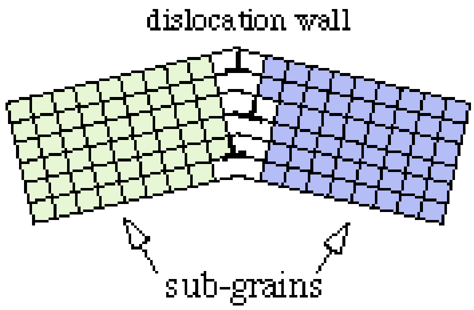


- stacking faults- are planar features where a
- loops if you take a dislocation line and follow it round and it joins back up with itself, this is known as a loop, and is by its nature made up of a combination of screw and edge dislocations, with a cylindrical volume of "slipped" crystal within the loop. As the loop grows, the volume of slipped crystal thus grows with it.



- Frank-Reed sources are "loop generators" that occur as impassable defects in a crystal hold up the passage of a dislocation. If two such defects occur as neighbours, an automatic loop generator is formed. This is what a dislocation Frank-Read source looks like. See Dislocation dynamics section in Lab 1 for further examples. This simulation shows one inclined slip plane with loops being generated continuously.

- tilt boundaries- sub-grain boundaries made up of arrays of edge dislocations



- twist boundaries- sub-grain boundaries made up of arrays of screw dislocations

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f) Rheology of dislocation glide:

ρ€=dislocation density = no of dn lines per cm^2 or total line length per cm^3

- near perfect artificial crystal $10^2 cm^{-2}$
- annealed or as grown crystal $10^5 cm^{-2}$
- cold worked crystal 10^8 to $10^{11} cm^{-2}$

$$\dot{e} = \rho \underline{b} \bar{V}$$

this is OROWANS EQN, where V = ave mobile dislocation velocity

$$\rho \propto \sigma^2$$

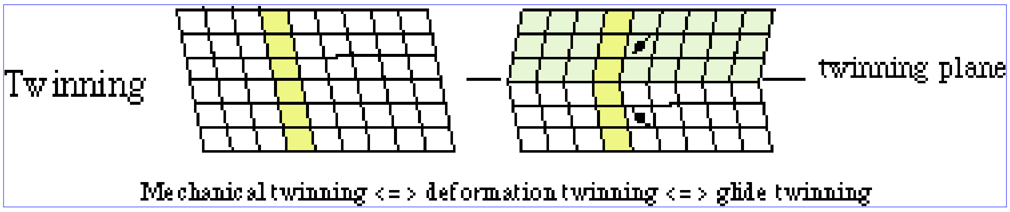
at low V, V is proportional to the stress which gives:

$$\dot{e} \propto \sigma^3$$

---

g)Twinning

Unlike dislocation glide, movement of a twin boundary significantly and permanently alters the orientation of the crystal. The orientation of the twin plane, and the misorientation across the twin boundary will be precisely the same for any particular type of twin, and the process of twinning is essentially instantaneous, there is not a gradual change in crystallographic orientation, as the twin boundary moves across a region, the crystal lattice flips, and a discrete increment of deformation is attained. Further deformation of the grain may cause more material to become twinned, but it does not further deform the twinned volume (at least not by the same type set, other twins, or other mechanisms may of course be activated). Deformation twins can often be distinguished from growth twins (that form during crystal growth) by being thinner, and having wedge shaped terminations. They are particularly important in the low temperature deformation of calcite, and the deformation of plagioclase. Here is a movie of twin development in bischovite, a hydrated magnesium salt, made by Janos Urai.



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h) Kinking

Kinking superficially looks like twinning, however the relationship between the misorientation across a kink band boundary, and the orientation of the kink band boundary nd the amount of deformation caused by the kink are not predictable. Micas often deform by kinking, which involves slip on the basal plane.

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h) Grain boundary sliding

The movement of one grain past another, in pure material this may be accomplished by dislocation or diffusive mechanisms.

A beautiful molecular dynamics simulation of copper nano-crystals undergoing grain boundary sliding during vertical extension was performed by Jakob Shiotz (J. Schiotz, F. D. Di Tolla, and K. W. Jacobsen, Nature, 391, 561 (1998)). Here the sphere shading relates to the local crystal structure: White atoms are in a perfect face centred cubic environment. Light gray atoms are in local hexagonal close packing order, which for example corresponds to stacking faults. Atoms in any other environment (in grain boundaries and dislocation cores) are colored dark grey.

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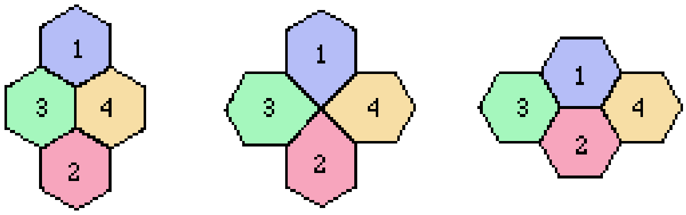
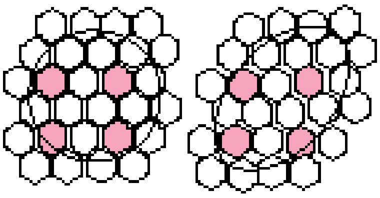
i) Other deformation processes:

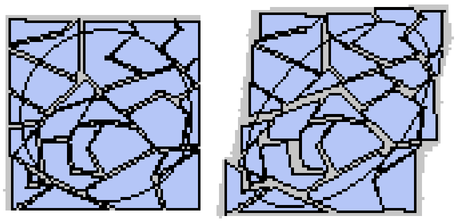
- neighbour switching
  The switching of grain relationships (needs grain boundary sliding and diffusion to cooperate to allow this).



- rigid body rotation- rotation of grain without any internal deformation. A ball undergoes rigid body rotation (or bulk rotation) when you roll it along the ground. Very rigid grains in a soft matrix will typically rotate in non-coaxial deformation regimes (see discussion on porphyroblasts in lecture 4). Similarly a feldspar lath in a granite melt can rotate with essentially no internal deformation if the melt is sheared.
- granular flow



- fracture- the brittle cracking of a mineral, often followed by sliding on or pulling apart of the fracture surfaces



- phase change- a change in the crystallography of the crystal, without a change in its bulk chemistry.
- Pressure Solution- The long-range (multiple grain) diffusive mass transfer of material. See lecture 5.

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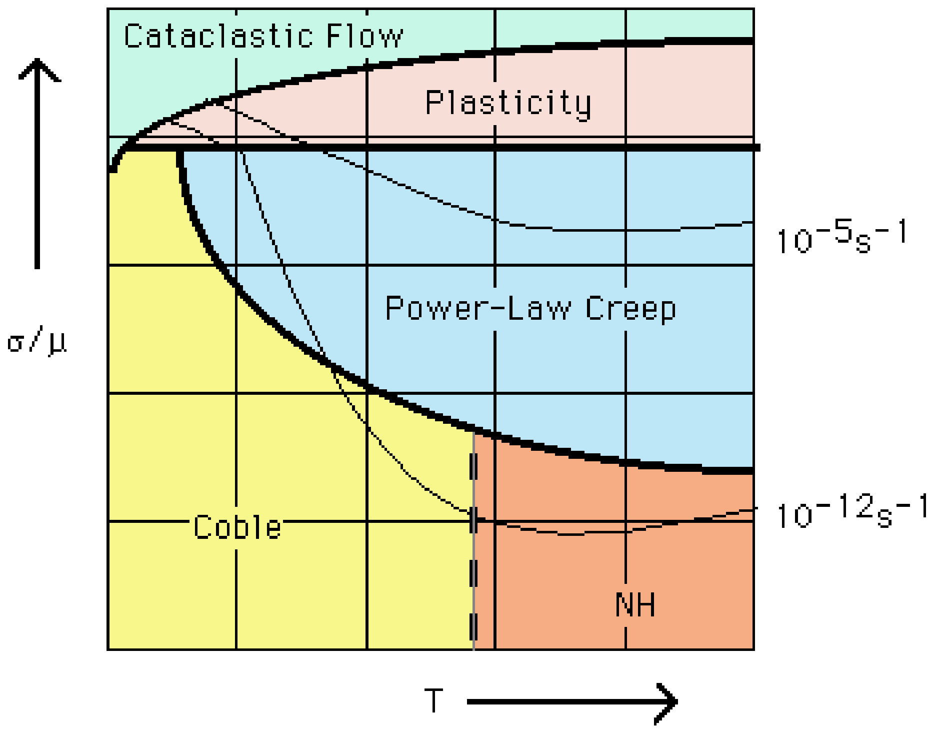
j) Deformation mechanism maps

These are graphs in typically stress-temperature space (but also grain size-temperature and others) which show which deformation mechanisms dominate under which conditions FOR A PARTICULAR MINERAL. They are contoured in strain rates, showing the strain rate that would be achieved by that process alone under the appropriate conditions. They only show dominance in terms of which mechanism is likely to account for the most strain, the label in any particular field does NOT mean that no other mechanism or process is active, and it does NOT mean that the microstructural development will be controlled by that labeled mechanism, in fact it does not even mean that the deformation mechanism is the dominant process in terms of microstructural evolution. It would be nice if we had general Microstructral process mechanism maps, an example of which is shown at the end of Lecture 3.



0.1mm deformation mechanism map

Lecture 2- Recovery, meta-dynamic recrystallisation & static grain growth

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VIEPS/Mainz Microstructure Course

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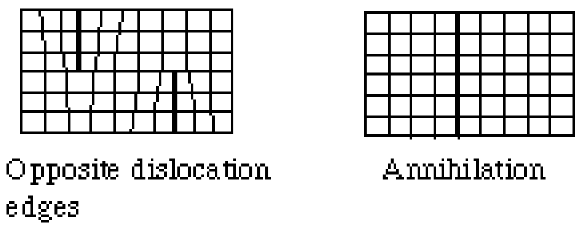
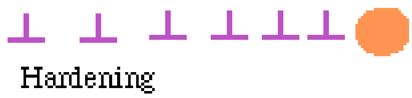
1) Recovery:

- So called because it describes the processes that lead to a recovery of mechanical properties, since deformation of polycrystals at low temperature typically leads to the material gaining in strength (because the dislocations get tangled and can no longer move freely). Recovery processes are enhanced at higher temperatures, and occur both during deformation and subsequent to it, but are typically swamped by deformation processes during deformation. There are a number of competing processes that can lead to the observation of a recovered mechanical state:

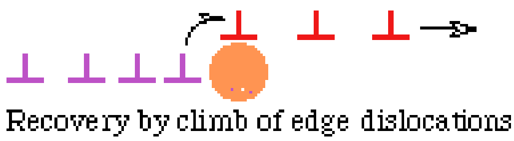
  - mutual annihilation when dislocations of opposite sign meet up exactly. The two half planes of each dislocation become a full plane, and the two dislocations disappear. In the following example cross-slip occurs to allow this to take place.



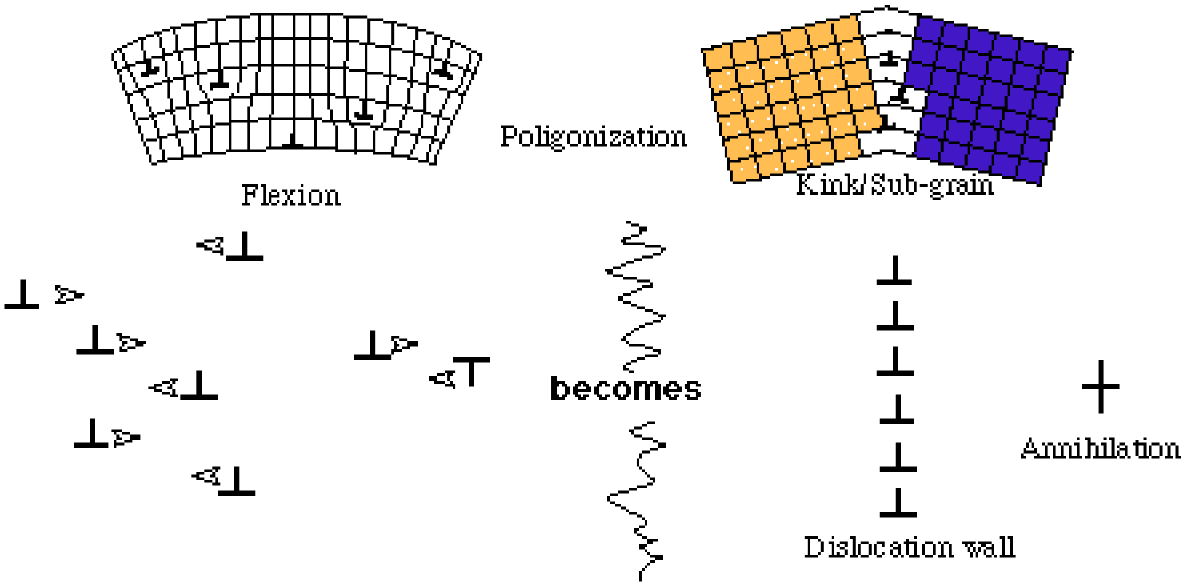
  - pile-ups when dislocations are held up by, for example another type of dislocation or an impurity, it just sits there, because dislocations of like sign repel each other, the next dislocation will "wait" in the queue behind the first one, and so on. Each dislocation adds to the stress on the object blocking the way, until, sometimes that object may be overcome, and the dislocations may move freely again. The longer the pathway for the dislocations to build up the larger the obstacle that can be overcome, hence the Hall-Petch law which says the yield strength is proportional to 1/grain size.



  - climb Another way of clearing an obstacle is to climb over it. Climb is easier at higher temperatures, as it is a diffusional process.



  - polygonisation The movement of free dislocations (those not bound up in dislocation arrays) will eventually bring them into existing dislocation arrays, this reduces the energy state of the system, and is thus more stable, and the formation of these sub-grain boundaries is a typical microstructural response to recovery processes.



- cross-slip Another form of dislocation motion can take place when the dislocation moves on a vector which is a combination of two or more existing slip systems. In this example double cross-slip occurs to avoid a fixed dislocation.

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2) Recrystallisation:

The formation & movement of sub-grain & grain boundaries (definition of Urai et al 1986). There are again a number of distinct but interacting processes that are involved in recrystallisation.

i) Rotation recrystallisation

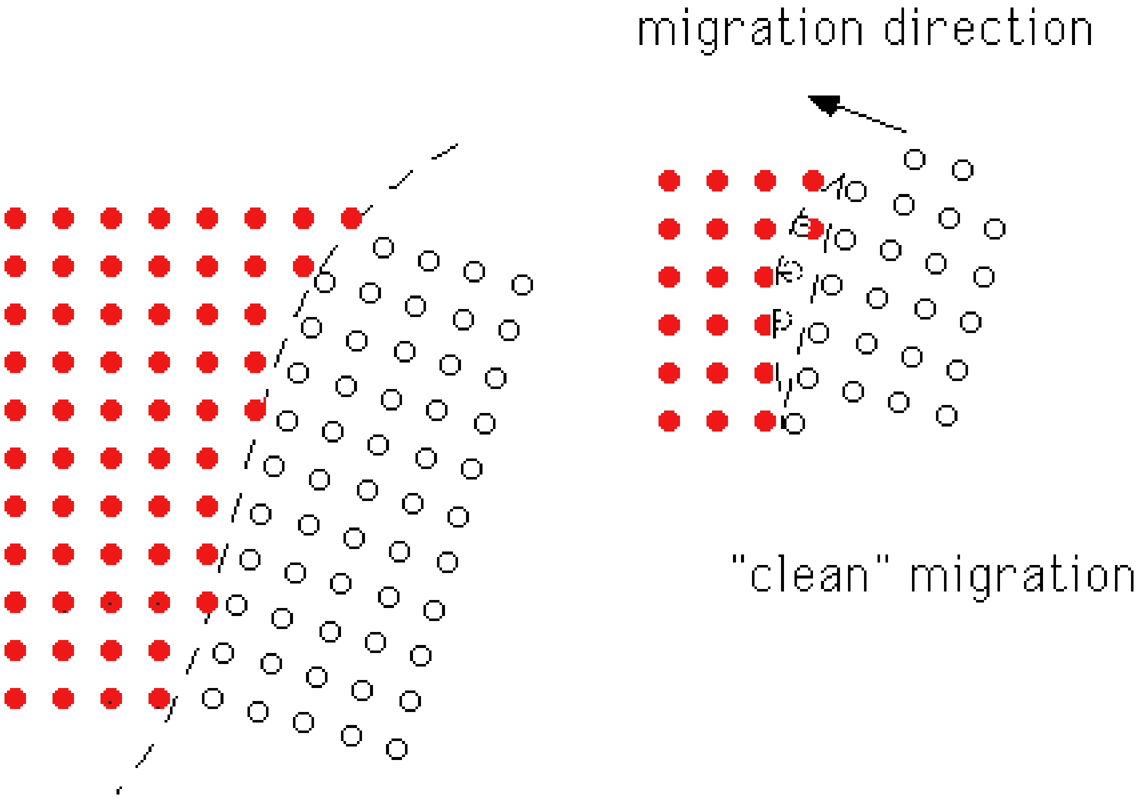
When a dislocation is added to a sub-grain boundary, it will change the angular mismatch between the two sub-grains. When dislocations of the same sign repeatedly become part of a single boundary, the two sub-grains either side become progressively misoriented with respect to each other, and eventually the mis-match may become large enough that the boundary becomes a grain boundary. The exact orientation at which this takes place is probably mineral dependent, however 10-15 degrees misorientation is commonly quoted.

ii) Grain boundary migration & pinning

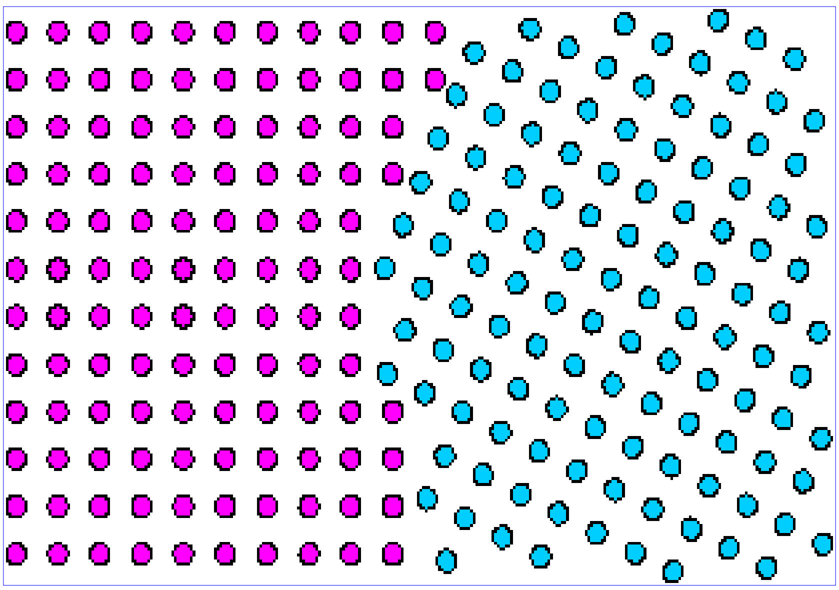
Grain boundary migration refers to the movement of the boundary separating two grains. The movement takes place by the diffusion of single atoms from one grain across the boundary to the other grain. This motion results in the migration of the boundary in the opposite direction to the diffusion direction. There are several driving forces for grain boundary migration, in decreasing order of magnitude they are chemical, strain energy (stored as dislocations), and elastic energy. The driving force for migration is the difference between, for example, the dislocation energy state either side of the boundary. The rate at which a boundary migrates is both a function of this driving force, and the mobility of the boundary, which is an inherent property of a material (but which varies according to temperature, the presence or absence of fluids, the nature of the boundary, and the impurity content of both the grains and the boundary).
In the examples below we distinguish grain boundary migration in "clean" and "dirty" systems. Clean systems, like metals, many sub-grain boundaries and perhaps grain boundaries between quartz grains in a granite, can have grain boundary migration involving only the local readjustment of atoms at the boundary, and in an impure system. Dirty systems such as a schist

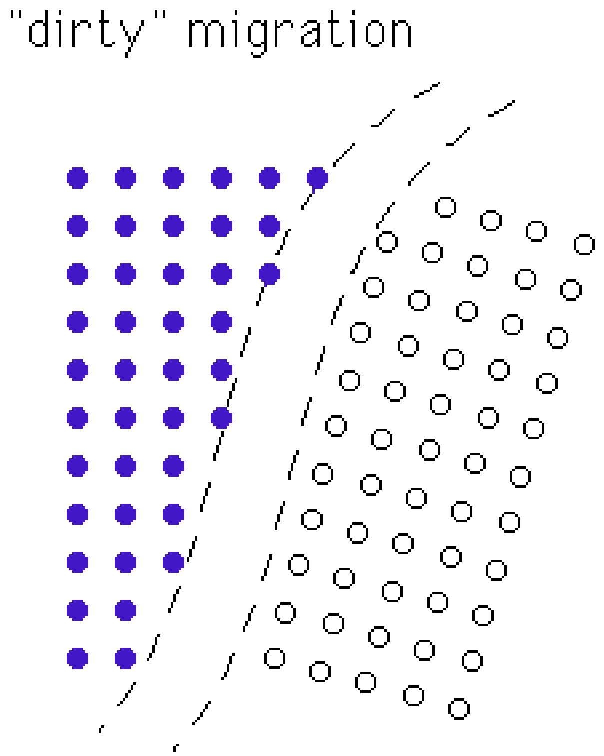
resulting from the metamorphism of a pelite, where the grain boundaries will be rich in impurities, or where the grains may not even be in physical contact, have to diffuse material across a grain boundary of finite width. Impure systems will probably have lower grain boundary mobilities (velocity = mobility * driving force) than pure ones.

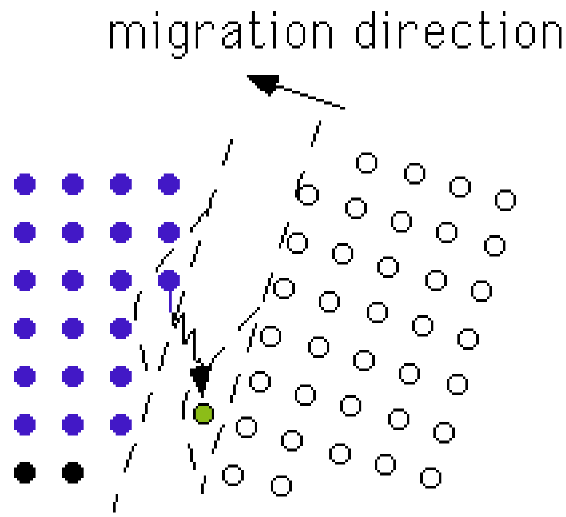
Second phase particles (small micas, for example) will hinder grain boundary migration by "pinning" the boundary locally. If there are enough particles in a rock, the grain size can be controlled entirely by the particle spacing.



Simulation of grain boundary migration in a clean system.



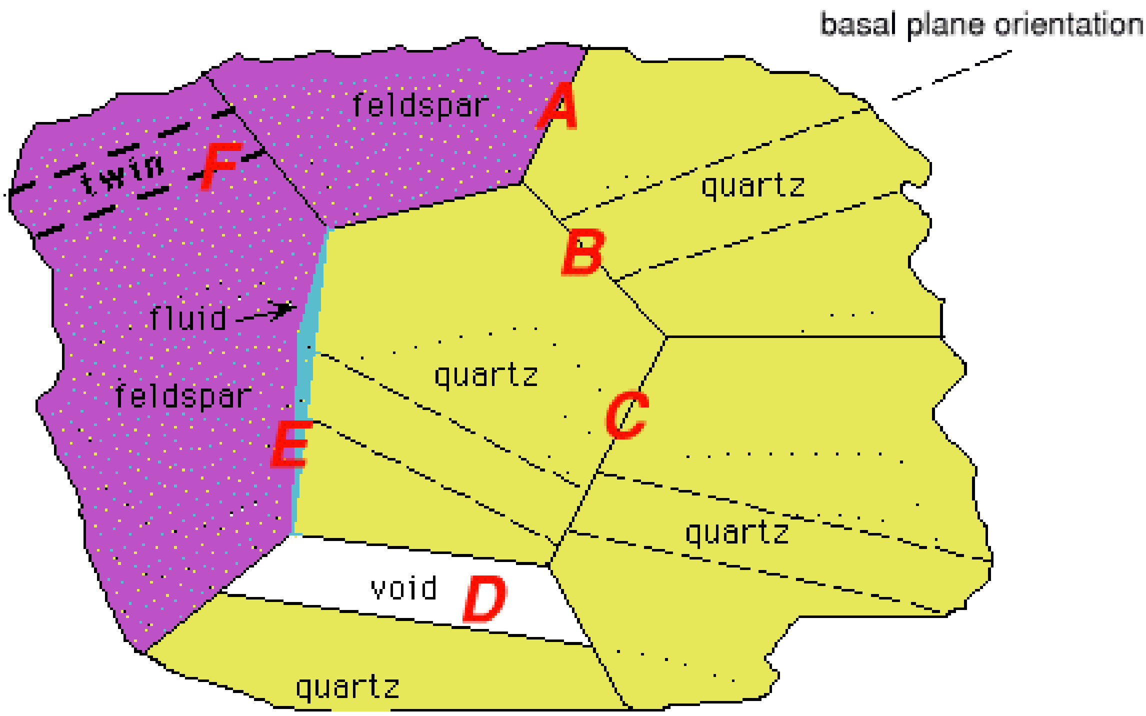




iii) What defines a (sub)grain boundary, and how do they vary?

In the following picture we can distinguish six different types of boundaries in a polycrystal that might be expected to behave differently:

A) A phase boundary between two different minerals.
B) A high-angle (high misorientation between the two crystal lattices) grain boundary between two grains of the same mineral.
C) A low-angle grain boundary between two grains of the same mineral.
D) A grain boundary between two grains of the same mineral, with a dilatant void separating them.
E) A phase boundary between two different minerals, with a dilatant void filled with a fluid.
F) A twin boundary within one different mineral.



iv) Static, Dynamic, Meta-dynamic Recrystallisation

These three terms refer to the processes of recrystallisation that occur without deformation, during deformation and following deformation respectively. The actual processes themselves are for the most part the same, but the driving forces that control them can vary enormously, so the resulting microstructures can look quite different.

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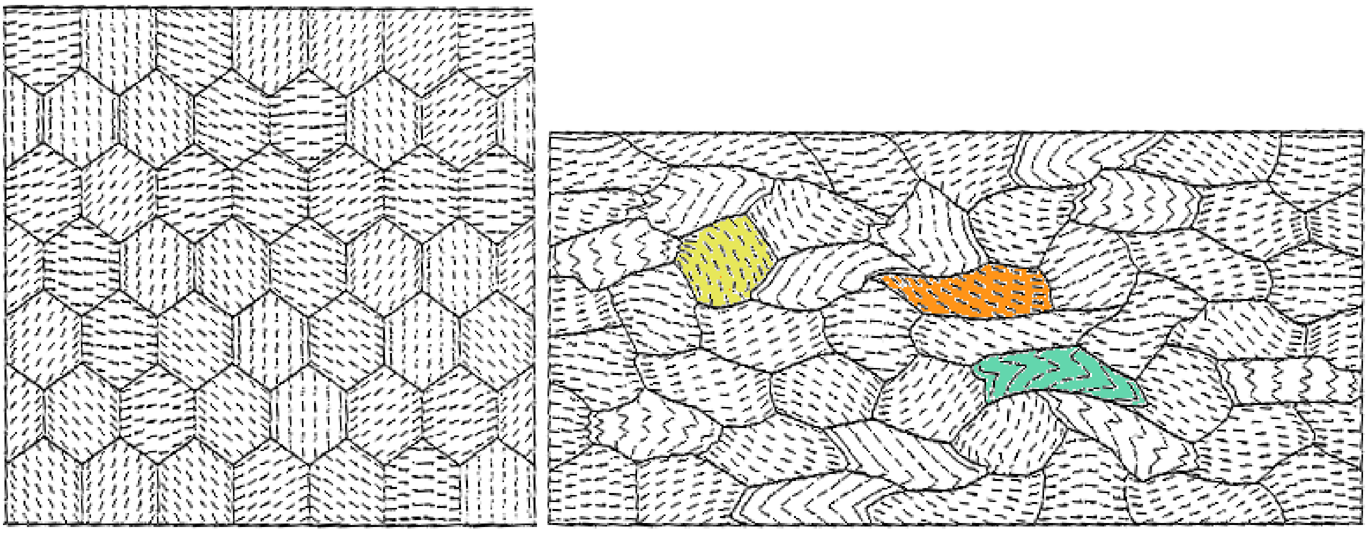
3) What makes two grain behave differently?

a) mineralogy Different minerals have different slip systems available for deformation, and can deform more or less easily by diffusional processes. As a result their mechanical properties can be quite distinct (even if they use the same deformation mechanisms).

b) crystallographic orientation Since during plastic deformation of a crystal the CRSS controls the movement of dislocations, grains which are well oriented for slip on a particular slip system will in principal be able to deform more easily than those whose slip system orientations result in low resolved shear stresses. The pair of images below are from Y. Zhang's PhD thesis and show a numerical simulation of deformation in a polycrystal with only one slip system, notice how in the second figure the three coloured grains have undergone virtually no deformation (yellow) a lot of deformation (orange) and a lot of deformation with internal kinking as well (green). The short lines within grains show the local slip system orientation.



c) shape The shape of any object will be an influence on its mechanical behaviour, elongate grains will be more prone to buckling than spherical ones, and if a series of elongate grains are all aligned, it makes it easier for them to deform by grain boundary sliding. Similarly elongate grains will have a mechanical coupling on them that will tend to rotate them with respect to the applied stress that spherical grains will not have.

d) neighbours The local neighbourhood relationships of grains will influence the local behaviour. If a weak mineral is surrounded by stiffer grains, it may be "shielded" by those grains and remain undeformed, even though it is inherently weak.

e) history As grains deform, their internal dislocation arrangement, shape and chemistry may change, which in turn leads to a change in mechanical properties.

f) grain size There are two main grain size dependent behaviours, one related to the Hall-Petch effect for plasticity, that makes smaller grains stiffer, the other for diffusional creep, that makes smaller grains less stiff.

g) grain boundary orientation certain grain boundary orientations allow easier grain boundary sliding, for example a brick wall texture in simple shear would allow easy grain boundary sliding because all the boundaries are aligned.

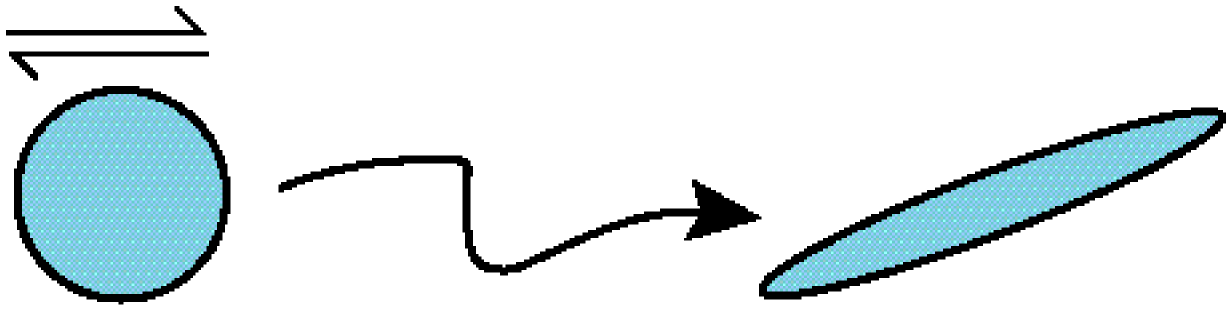
Lecture 3- Grain shape & crystallographic fabric development

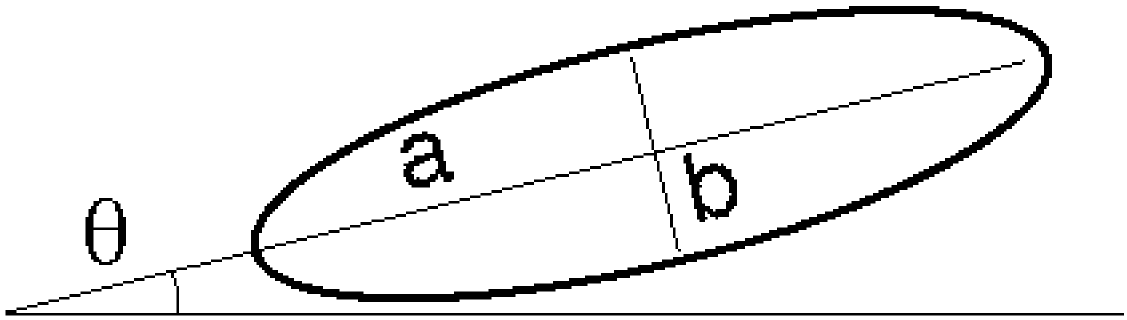
VIEPS/Mainz Microstructure Course

1) Grain shape foliations Grain shape foliations are the preferred alignment of elongate grains (the particle orientations of Panozzo 1983), or the preferred orientation of grain boundaries (the surface orientations of Panozzo 1983).

Grain Orientations   (Particle Orientations)

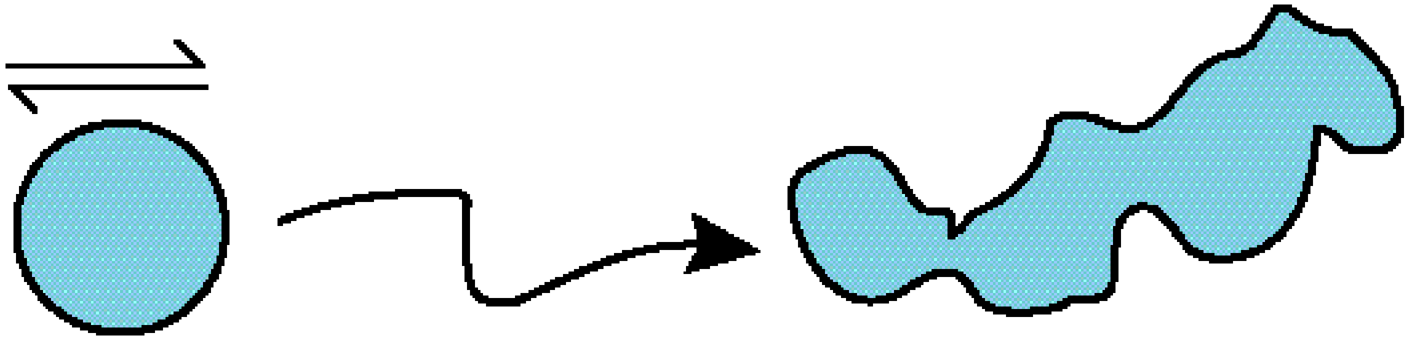
These can be measured by measuring the longest axis of each grain in a thin section.

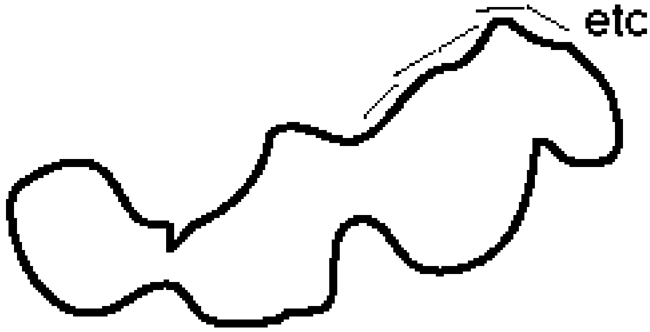




Grain Boundary Orientations (Surface Orientations)

These can be measured by breaking the grain boundaries into short line segments and measuring the orientation of each segment. For many rocks the two techniques will give similar results, however this does not have to be the case.

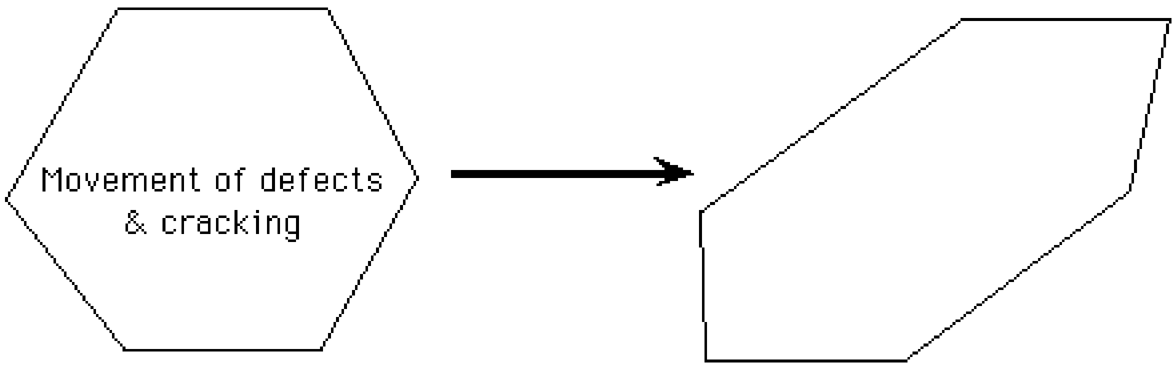




2) Processes that affect the development of a grain shape foliation

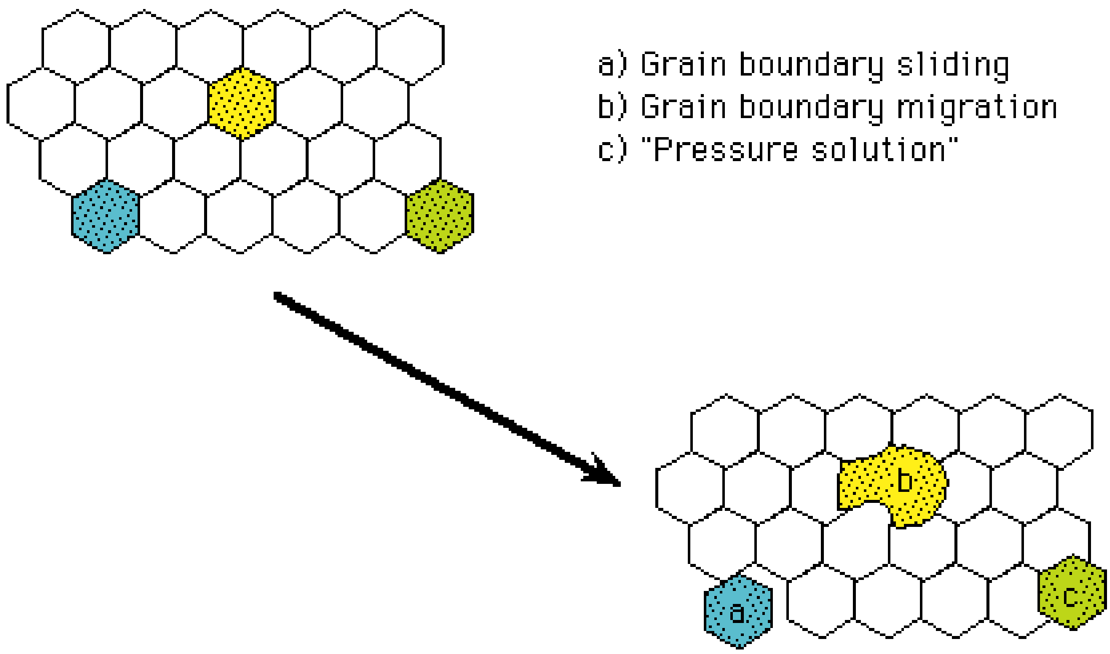
- The picture below shows the competing processes involved in grain shape foliation (GSF) development. Not all of these processes lead to a strengthening of the GSF, see Deformation Mechanisms table for further details.

Intra-crystalline



Point defects:	diffusional creep (Coble or Nabarro-Herring creep)
Line defects:	dislocation glide climb
Plane defects:	rotation recrystallisation sub-grain boundary migration twinning

Inter-crystalline



a) Mica foliations

- The two early models for mica foliation development were proposed by March and Jeffreys
- March proposed that foliations formed by the micas acting as passive strain markers, ie that they deformed along with the matrix. This implies that the micas changed shape during deformation.
- Jeffreys proposed that the foliations formed by the micas acting as rigid objects that

rotated as the matrix deformed. This implies that the micas kept their shape during deformation.

- Slaty Cleavage- Slaty cleavages are primary cleavages which are now believed to form by a combination of processes: bend of micas, rigid body rotation, recrystallisation of existing micas and growth of new micas.
- Crenulation Cleavage- Crenulation cleavages are secondary cleavages that develop when a primary cleavage is shortened sub-parallel to its existing foliation plane. Crenulation cleavage development involves micro-buckling of the original foliation associated with rigid body rotation of micas, diffusive mass transfer of quartz away from the limbs to the hinges of the micro-buckles

- Pressure Solution Cleavage- The formation of a cleavage as closely spaced stylolites

b) Foliations in non-platy minerals Pannozzo1983

- Processes causing grain shape changes:

  Intra-crystalline processes:

  - Dislocation Glide- leads to internal deformation of individual grains, and hence of grain boundaries
  - Twinning- leads to internal deformation of individual grains, and hence of grain boundaries
  - Climb- can lead to internal deformation of individual grains, and hence of grain boundaries
  - NH Creep- leads to internal deformation of individual grains, and hence of grain boundaries
  - Kinking- leads to internal deformation of individual grains, and hence of grain boundaries
  - Cracking- leads to generation of new grain boundaries, their orientation can be either crystallographically controlled or by orientation of stress field, or some combination of both.
  - Rotation Recrystallisation- newly formed subgrains are typically fairly equant, so if these become sufficiently reoriented to become new grains, they will degrade the grain shape foliation

  Grain boundary processes

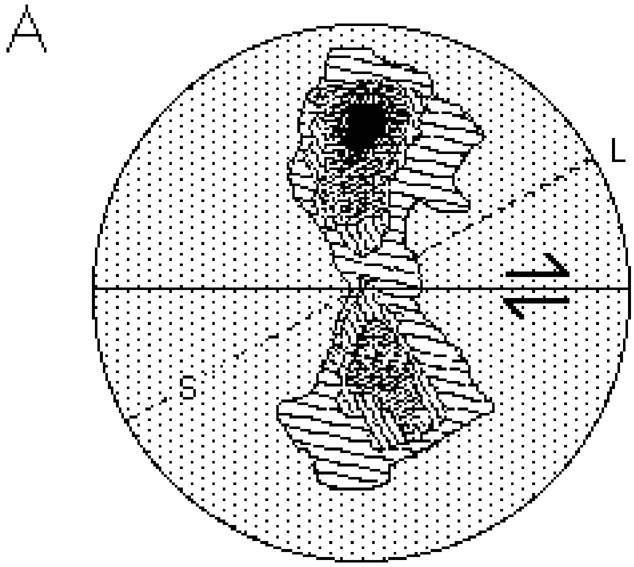
  - Grain Boundary migration. Typically reduces the strength of the grain shape foliation, either during deformation, when dislocation density contrasts drive GBM or after deformation where in addition the surface energy driving force may be important.
  - Coble Creep- can lead to change of shape of individual grains, and hence of grain boundaries

---

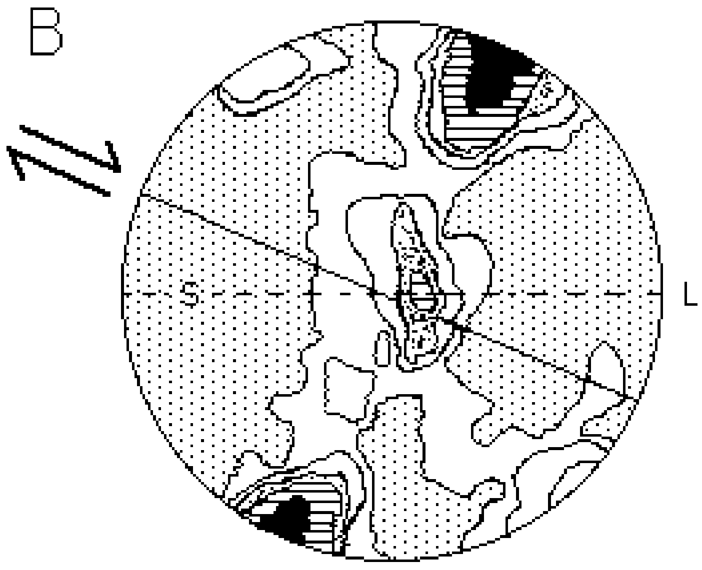
2) Crystallographic preferred orientations

Crystallographic preferred orientations (CPO), are also known as textures, petro-fabrics, fabrics

& lattice preferred orientations. The term refers to the observation that in many deformed rocks there is a clustering of crystallographic orientations. The figures below are contoured equal-area stereographic projections of the c-axes of quartz grains showing the relationship of the fabrics wrt the foliation (S) and the lineation (L)



Brunel, 1980



Brunel, 1980

Any processes that systematically changes the orientation of a grain, or part of a grain, or changes the size of a grain can potentially lead to a modification to the pattern of orientations.

a) Lattice rotationsEtchecopar 1977, Lister et al 1978

Processes causing lattice reorientations:

Intra-crystalline processes:

- Dislocation Glide- the glide of dislocations on slip planes generaly leads to the reorientation of the crystal lattice.
- Twinning- twinning inherently involves the reorientation of tabular volumes within a crystal, and as these tabular bodies can widen and coalesce with subsequent deformation, the whole grain can have its lattice orientation altered

- Kinking- again tabular volumes will be reoriented
- Rotation Recrystallisation- reorientation of sub-grains as a result of addition of dislocations of like sign to sub-grain boundaries

Inter-crystalline processes

- Grain Rotation- rotation of a whole grain will necessarily reorient its lattice

b) Grain Boundary Migration Kamb 1972, Jessell 1988

- Grain boundary migration in deforming rocks is driven by contrasts in dislocation densities. Since grains with different crystallographic orientations will deform using different slip systems, their internal microstructures will be different. In particular the dislocation densities will be at least in part crystallographically controlled, so that there is a crystallographic control on which grains will grow at the expense of their neighbours.
- At low temperatures grains which find it difficult to deform because of their orientation tend not to deform at all, and as a result they have lower dislocation densities, and tend to be preserved as augen grains.
- At higher temperatures, more grains will deform (since the CRSS of all slip systems goes down with increasing temperature), and in this case the grains which deform at the lowest applied stresses will have the lowest dislocation densities. As a result grains which find it hard to deform because of their orientation will be consumed by their neighbours.

c) Diffusional processes - See Bons abstract in BASEL microstructure conference volume for explanation of how this might work.

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3) Grain Size vs stress relationship

It is a common experimental observation that there is an inverse relationship between the median grain size in a deforming polycrystal and the applied deviatoric stress. This occurs because there is a balance between those processes leading to an increase in grain size, such as grain boundary migration, and those processes leading to a reduction in grain size, such as rotation recrystallisation.

In reality using this relationship can be quite difficult, since metadynamic processes such as grain growth can affect the observed grain size, and even if it appears that no such modification has taken place, we have to be able to demonstrate that the observed grain size was formed during steady-state flow. See Twiss

---

4)Dislocation Creep Regimes in Quartz Aggregates

Greg Hirth & Jan Tullis 1992 (JSG 14, 145-159)

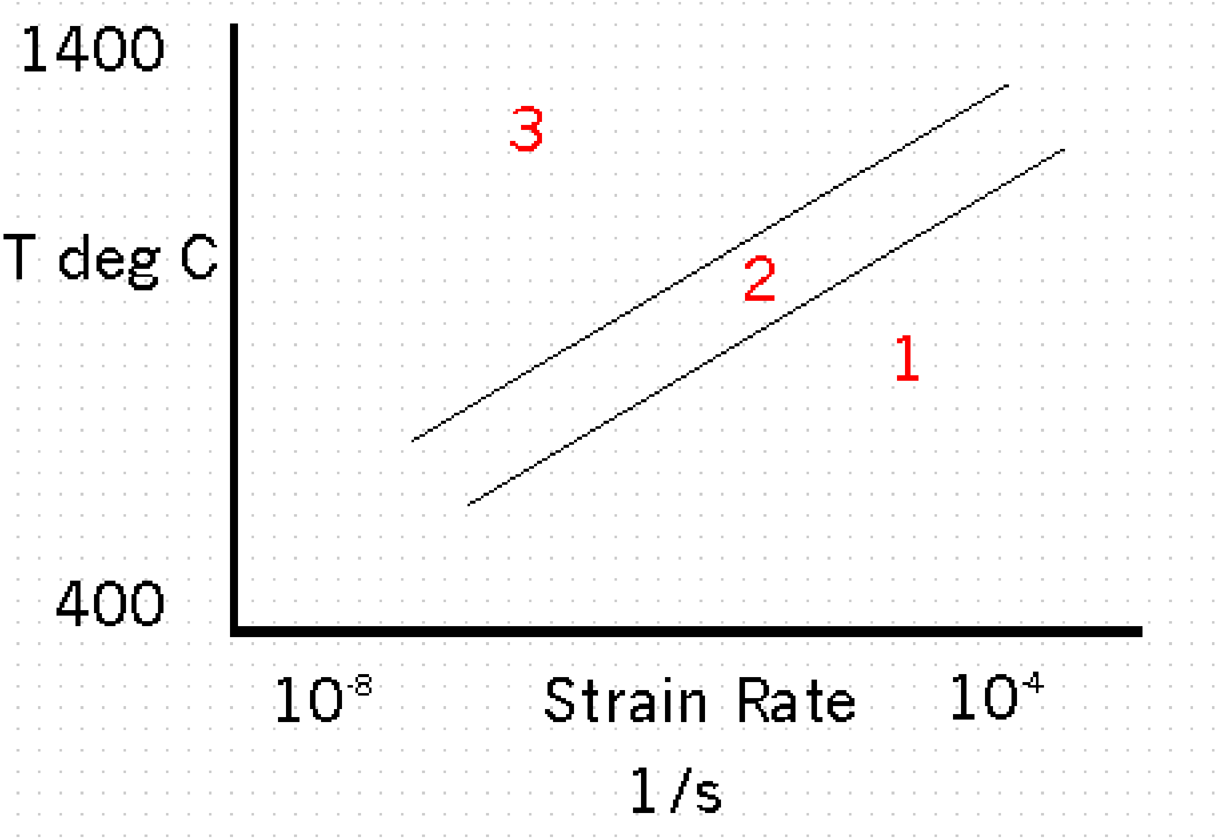
1) Dislocation climb difficult, low grain boundary mobilities, high dislocation density contrasts; leads to dislocation glide accommodated by recovery and grain boundary migration.

2) Rate of dislocation climb increases, rotation recrystallisation dominates.

3) Mobility of grain boundaries increases, grain boundary migration and rotation

recrystallisation both active.

Graph of Creep Regimes in experimentally deformed "as-is"quartzite



Lecture 4A- Metamorphism and deformation

VIEPS/Mainz Microstructure Course

A history of a mountain belt or other tectonically active area often includes both metamorphic and deformation events. The combined analysis of deformation textures and metamorphic textures is essential to reconstruct a full geological history, in particular the relative timing of deformation events with respect to metamorphic events. Porphyroblasts are the main structures used to study deformation in relation to metamorphism.

Metamorphic petrology -> P-T-t path

+ deformation events sequence -> P-T-D-t path

Porphyroclast <-> porphyroblasts

Porphyroclasts and **porphyroblasts** are both relatively large crystals in a finer grained surrounding (matrix).

Porphyroclasts are large grains that remained large while their surrounding matrix became fine grained (clasis = breaking). Feldspar augen (=eyes) in a recrystallised fine grained quartz+fledspar matrix are common and typical examples.

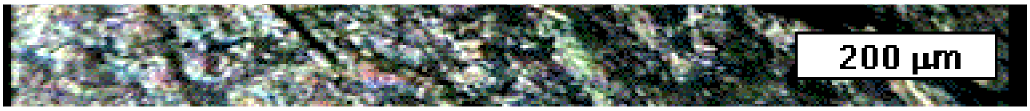
Porphyroblasts are new-grown metamorphic minerals that grow over pre-existing minerals (blasis = growing).

Some terms for the shape of porphyroblasts

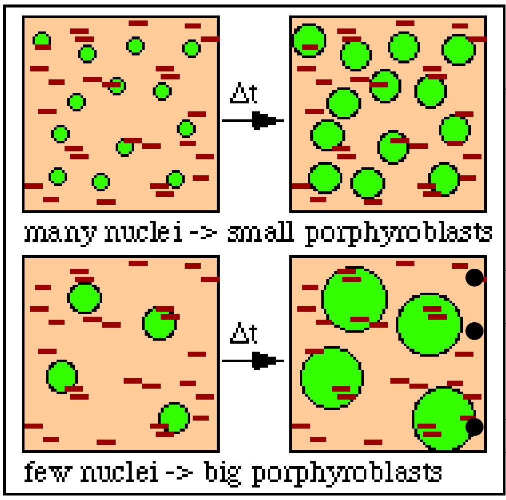
There are several terms that describe the shape of porphyroblasts:

idioblastic: porphyroblast which has grain boundaries controlled by its own crystallography

xenoblastic: porphyroblast which does not have grain boundaries controlled by its own crystallography.



Blastesis



Once P-T-etc. conditions are favourable for a metamorphic mineral to grow, nucleation can start. The small nuclei have a relatively high surface energy, which forms an energy barrier for their growth. The number of nuclei and their survival rate determines whether many small or a few large porphyroblasts form. This number depends on:

- the availability of favourable nucleation sites;
- the driving force for the metamorphic reaction (overshoot of PT-conditions)
- transport rate of elements that form new mineral and elements that have to be removed to make space available

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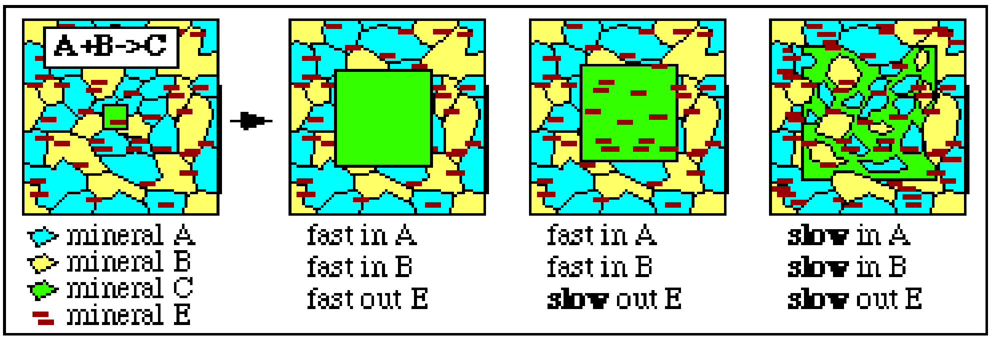
Inclusion trails

To form and grow a new metamorphic mineral grain:

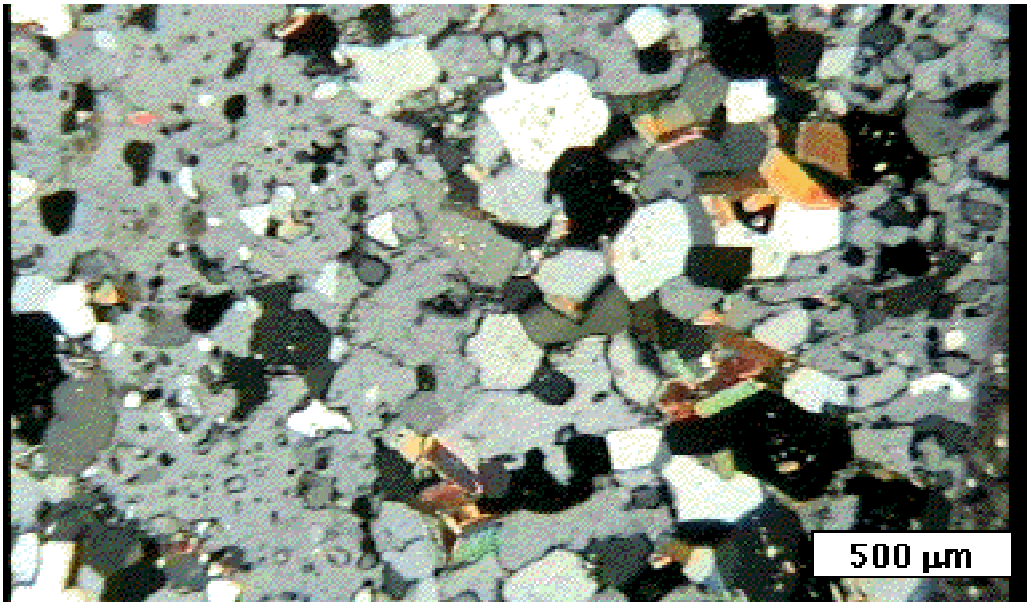
(a) the right mix of elements that form the mineral must get to the grain

(b) other elements have to be taken away from the grain

- If **(a)** and **(b)** are both fast enough, no inclusions are incorporated
- If **(b)** can't keep up with **(a)**, inclusions are incorporated of minerals that do not contribute to the metamorphic reaction
- If **(a)** is too slow, even inclusions of minerals that do contribute to the reaction are incorporated.

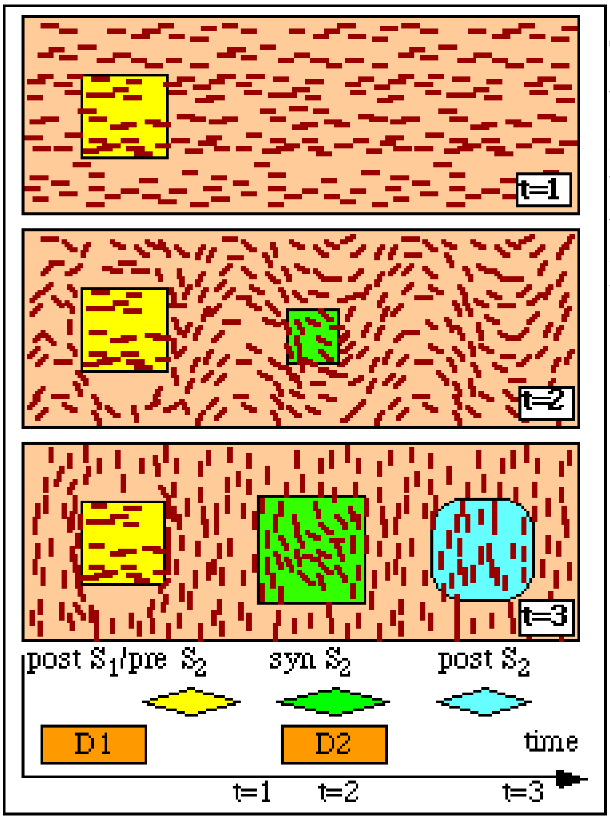


Some porphyroblasts are full of



inclusions. These are called poikiloblastic. The example here is of big cordierite crystal full of quartz and biotite inclusions.

Inclusion trail - foliation relation ships



The usual rigidity of the porphyroblasts protects the inclusion trail pattern from further deformation. Porphyroblasts with inclusions thus provide a frozen-in picture of the foliation at the time of their growth. This allows determination of the timing of growth (phases) relative to deformation or tectonic phases.

pre-tectonic

- The inclusion pattern is random, indicating no foliation at time of blastesis
- The younger foliation may be deflected around the porphyroblast

inter-tectonic

- The inclusions are aligned according to a foliation that was overgrown by the blast
- The inclusion pattern bears no relation with the foliation outside the porphyroblast
- The younger foliation may be deflected around the porphyroblast

- Inclusion trails and outside foliation are discontinuous

syn-tectonic

- Inclusion trails and outside foliation are continuous
- Inclusion pattern and outside foliation are similar, but inclusion trails may preserve outside foliation in an early stage of development.
- Gradual transition of pattern and orientation of inclusion trails from core to rim of porphyroblast
- Orientation of inclusion trails in core of porphyroblast may have different orientation due to rotation of porphyroblast during its growth (eg 'snow-ball garnets')
- Possible deflection of foliation outside porphyroblast

post-tectonic

- Inclusion trails and outside foliation are completely continuous and similar
- No deflection of foliation outside porphyroblast

See Passchier & Trouw 1996, pp 153-168 for more pictures of different classes of porphyroblasts

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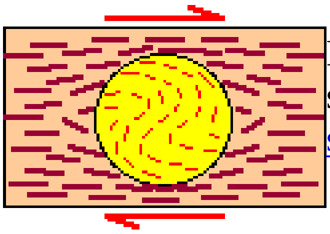
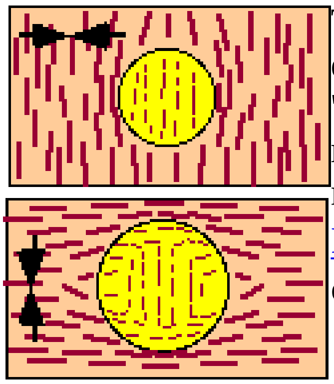
Complications

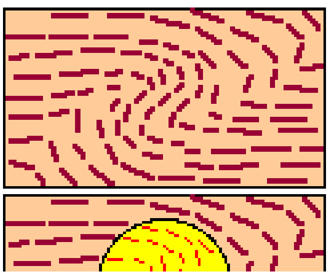
Rotating / non-rotating porphyroblasts



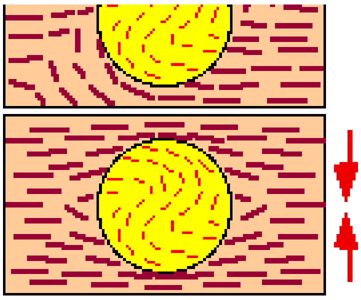
Rigid objects may rotate when deformation is non-coaxial. This can explain the spiralling or oblique inclusion trails in syntectonic porphyroblasts (as in snowball garnets).



The rotation of rigid objects is however inhibited if the object deflects the deformation around a lense-shaped region. This partitioning of strain can lead to 'millipede structures', which can give the appearance that the porphyroblast rotated during growth. The figure shows an example of the formation of a millipede structure by two shortening events at right angles.(see Bell *et al.* 1992, Passchier *et al.* 1992 and Passchier & Trouw 1996 for discussion of this controversial topic)



Apparent rotation or syntectonic growth can also be due to porphyroblasts growing over complicated foliation patterns, such as micro-folds or crenulations (called helicitic texture)



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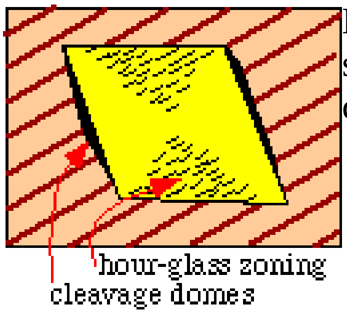
false inclusion trails

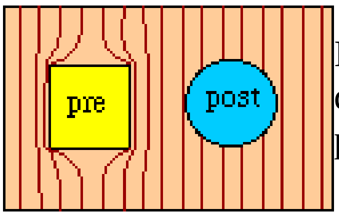
Care should be taken that 'false' inclusion trails are recognised. Such inclusions are usually crystallographically controlled and of course say little or nothing about the relation between growth and foliation development.

- exsolution features (perthite, antiperthite)
- healed cracks
- growth inclusions
- retrogressive alteration

No inclusions



Not all porphyroblasts have inclusion trails. Also, porphyroblasts can sometimes incorporate inclusions during some of their growth stages or only in crystallographically determined sectors (sector zoning and hour-glass zoning).



In the absence of inclusions, the relative timing of blastesis and foliation development can often be determined by the deflection of foliation around porphyroblasts

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Continue with lecture 4.b, Shear zones and kinematic indicators

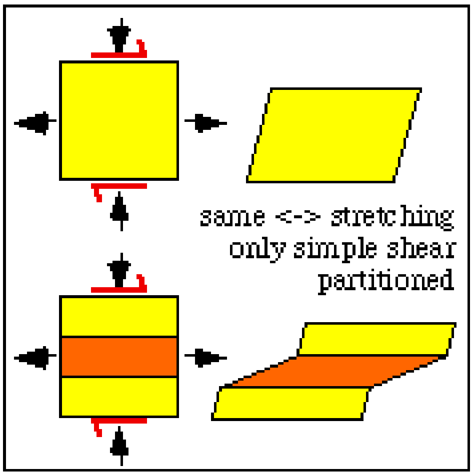
Lecture 4B- **Shear zones and kinematic indicators**

VIEPS/Mainz Microstructure Course

Shear zones are planar zones of localised deformation.

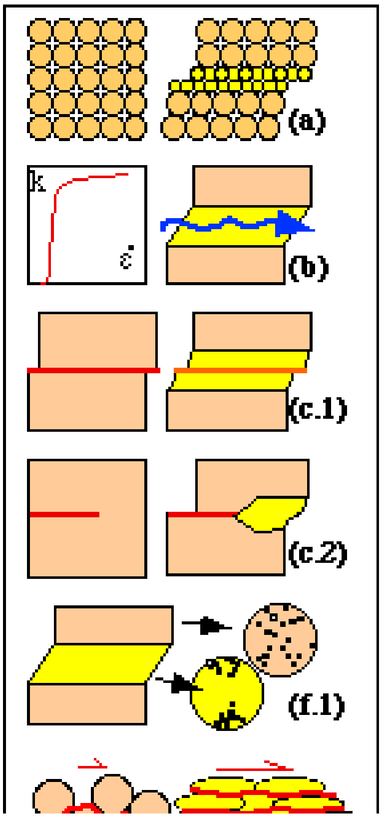
shear zones are weaker than country rock.

- deformation induced localisation
- different starting material



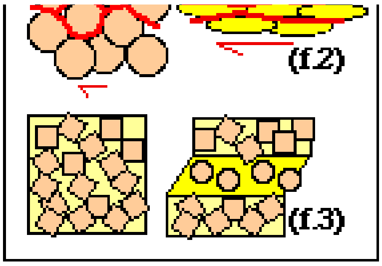
Typically, there is a strong tendency towards non-coaxial (simple shear) deformation within the shear zone. This because of compatibility of strain rate and stress:

- normal stress across a plane equal
- parallel stretching across a plane equal
  simple shear component can be partitioned



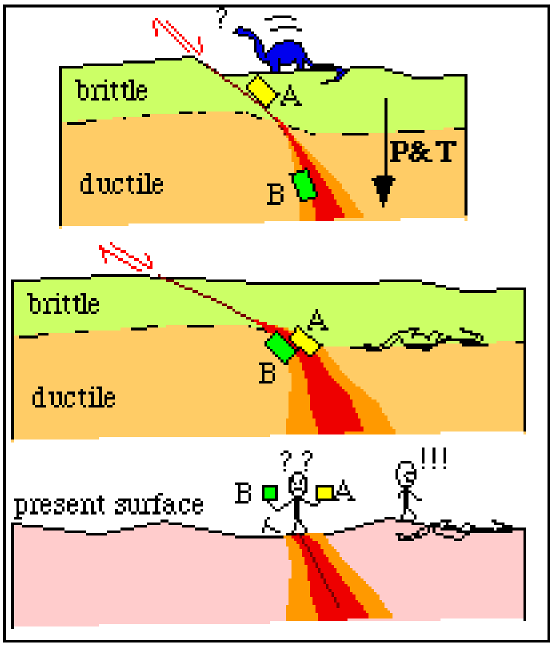
Localisation causes

- **(a)** Changes in grain size, with grain size sensitive deformation mechanism or mechanism switch
- **(b)** Influx of fluids
  - Enhanced permeability during deformation (dilatancy)
  - Shear zones often associated with retrograde metamorphism
  - Hydrolitic weakening in quartz (micro-cracking, H_20 in lattice)
- **(c)** Previous brittle faulting or ductile shear in extension of brittle fault zone
- **(d)** Shear heating giving thermal weakening
- **(e)** Transformation plasticity: metamorphic reaction enhances deformation and reaction softening where a new metamorphic mineral is softer or finer grained than the old one
- **(f)** Geometric weakening
  - Development of CPO



  - Development of grain shape foliation & domainal fabric
  - Rearrangement of mineral distribution & shape (frame-work collapse)
- **(g)** Recrystallisation

Crustal levels & mechanisms



Deformation mechanisms & localisation behaviour varies with P,T, etc.

Shear zones may have long history and cut through large section of the crust.

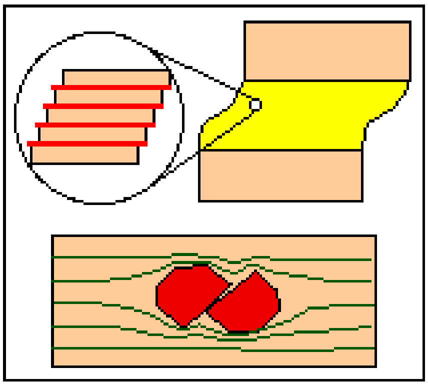
In general from upper to lower crust:

- brittle
- brittle-ductile transition
- ductile

Brittle: displacement variation discontinuous

Ductile: displacement variation continuous

Scale is important: small scale brittle can be large scale ductile



At same conditions one rock type or mineral may have brittle behaviour and another ductile.

Within one shear zone, deformation structures may vary over time and in space.

Different parts of the same shear zone (hanging wall / foot wall) may have different histories of deformation conditions.

Shear along shear zone may vary within one deformation event and even more when shear zone is reactivated (opposite senses of shear very well possible)

Result can be a wide variety of structures and overprinting relationships

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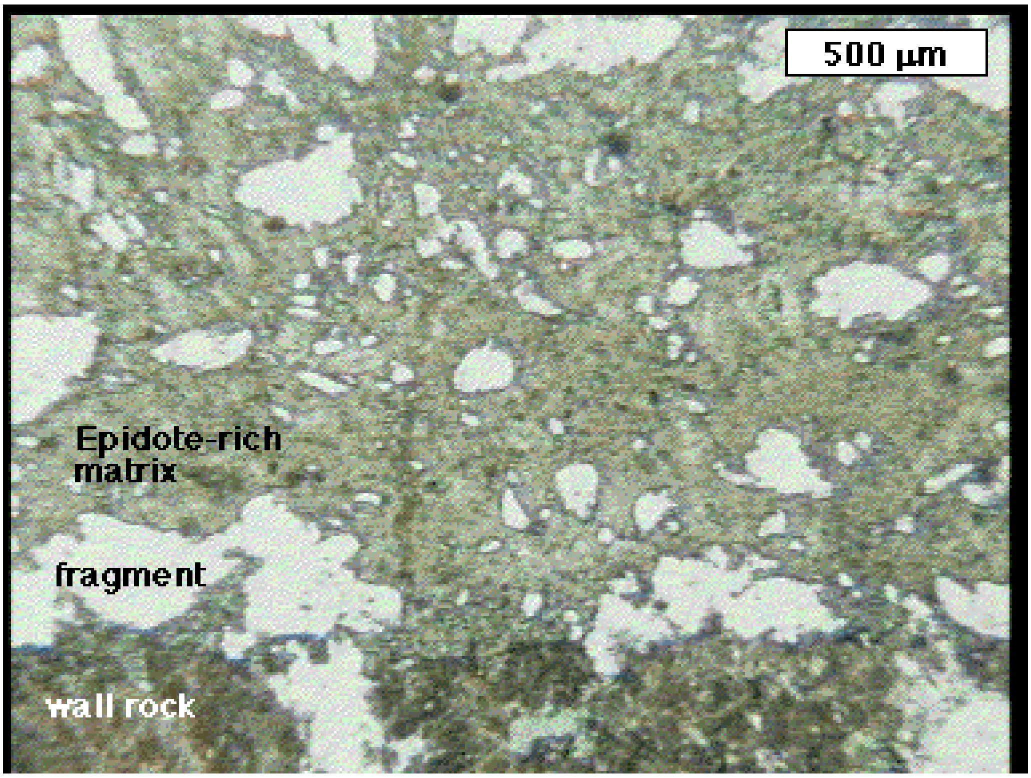
Main types of shear zone rocks from shallow to deeper levels

Brittle fault rocks

fault breccia (cohesive / incohesive): >30% angular fragments

cataclasite (cohesive / incohesive): <30% angular fragments

fault gouge: very few isolated fragments in very fine matrix



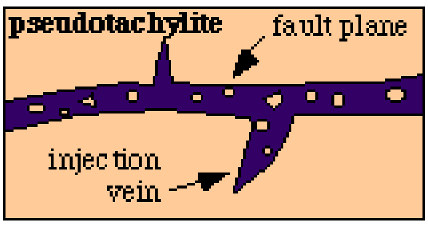
A cohesive cataclasite with quartz fragments in a cohesive epidote-rich matrix.

General reduction in grain size due to brittle processes (breaking of grains, "milling"). At very shallow levels the fault rocks can be **incohesive**. Dissolution/precipitation processes can contribute to the deformation and cement grains together: **cohesive** fault rocks.

Associated (micro-) structures:

- fault planes, shear fractures (at variety of scales)
- foliations (mica alignment, compositional, shear fractures)
- polished surfaces, grooves, striations
- veins, stylolites, slickensides

Pseudotachylite



Pseudotachylite: melting on fault plane during very rapid movement.

- (dark) glass or divitrification structures & spherulites
- injection veins
- Sharp contact with wall rock
- evidence for melting in the form of corrosion or complete melting of certain minerals
  Dark very fine grained cohesive cataclasites & gouges can look very similar to pseudotachylites

Ductile fault rocks

Mylonites are zones of strong to extreme localisation of ductile deformation.

- Localisation tends to decrease with metamorphic grade:
- upper extent ductile regime: narrow, extremely fine grained mylonites
- deeper: wide shear zones, gneisses to striped gneisses (coarse grained)

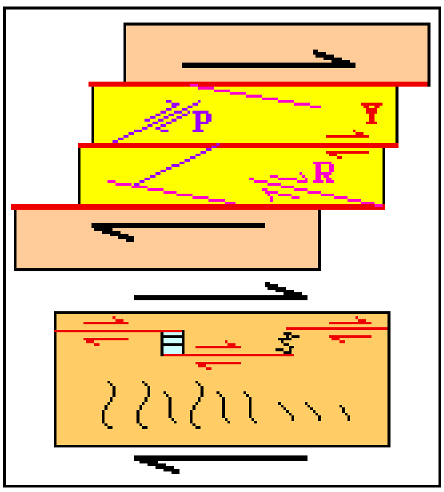
Typical ductile shear zone rock type: **mylonite**.

- fine grained due to deformation (recrystallisation, not brittle 'milling')
- normally well foliated (S-mylonite)
- often with linear shape fabric or stretching lineation (L-/LS-mylonite)
- containing remnants of coarser protolith: porphyroclasts
  - 10-50% matrix: **protomylonite**
  - 50-90% matrix: **(meso-) mylonite**
  - >90% matrix: **ultramylonite**
- planar zones, straight or anastomosing
- can occur in mylonite zones with several or many mylonites

High to extreme strain in predominantly simple shear:

- monoclinic symmetry of structures
- transposition of structures towards foliation & lineation

Shear zone microstructures & kinematic indicators

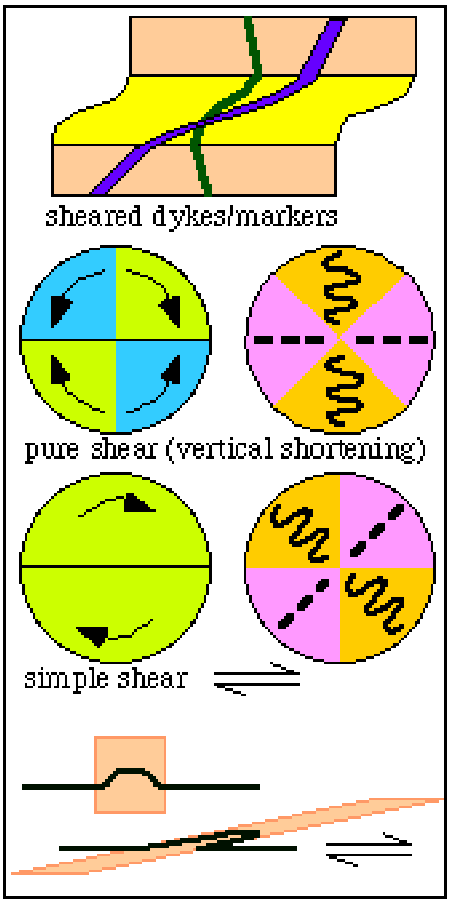


Brittle structures

Riedel shears (Y, P, R, R' - shears)

veins, vein arrays, fibres

stepped faults



passive markers

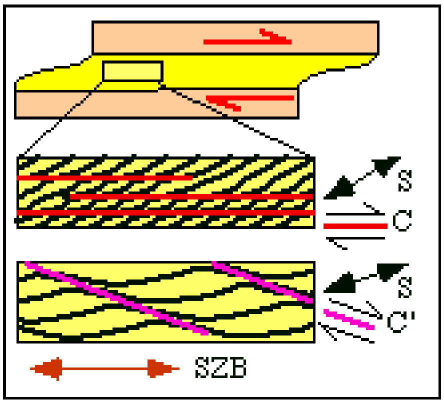
layers/dykes, etc larger than shear zone. Important to know shear direction (lineation) and take into account orientation of marker relative to shear zone

vein arrays (folding & boudinage). Rotation, stretching (boudinage) and shortening (folding) depends on orientation w.r.t. deformation. Shortening and stretching is possible during progressive deformation, but also take into account variations over time of applied deformation

sheath folds. Extreme strains can shear out any irregularity in layering into a tubular fold. Fold axes, like most other fabric elements get transposed towards flow plane (S) and flow direction (L). Active buckling and rotation enhances formation of sheath folds. Fold asymmetry can indicate shear, but be careful: original orientation of plane & different asymmetry on limbs of larger scale fold.

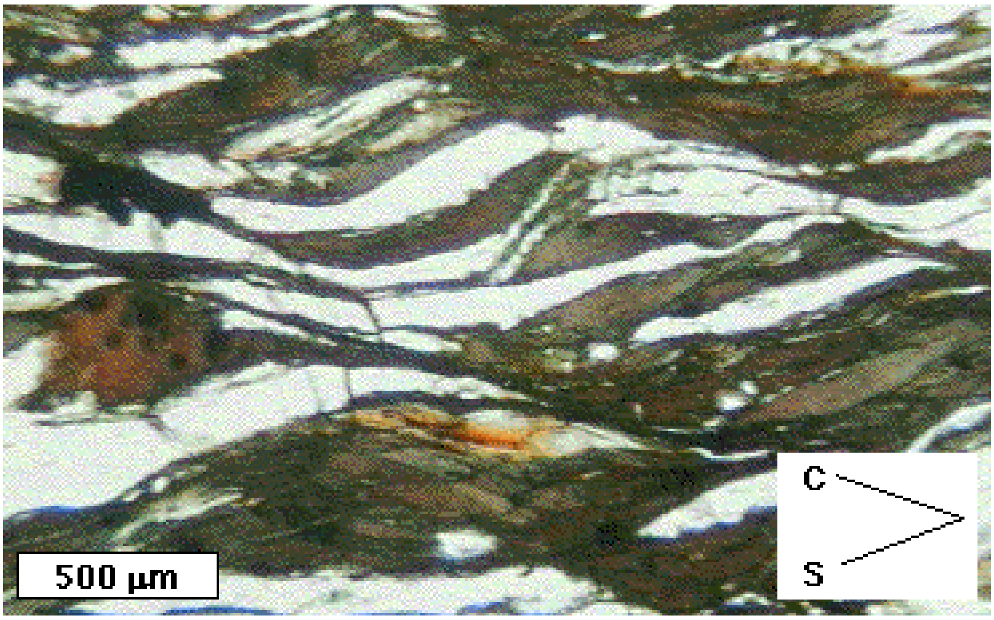
Shear bands & oblique foliations

Shear bands are small micro- or sub-shear zones in larger scale shear zone, i.e. small scale localisation or strain partitioning structures. They may look similar but are not the same as crenulation cleavages, which normally develop normal to shortening. (-> extensional crenulation cleavage (=shear bands) versus compressional crenulation cleavage).



- **S** = main foliation (schistosité), often oblique to shear zone boundary (SZB)
- **C** = shear bands (cisaillement) parallel to SZB.
- **C'**= shear bands oblique to SZB

C"=counterpart of C' in conjugate set; C" at high angle to SZB (rare)



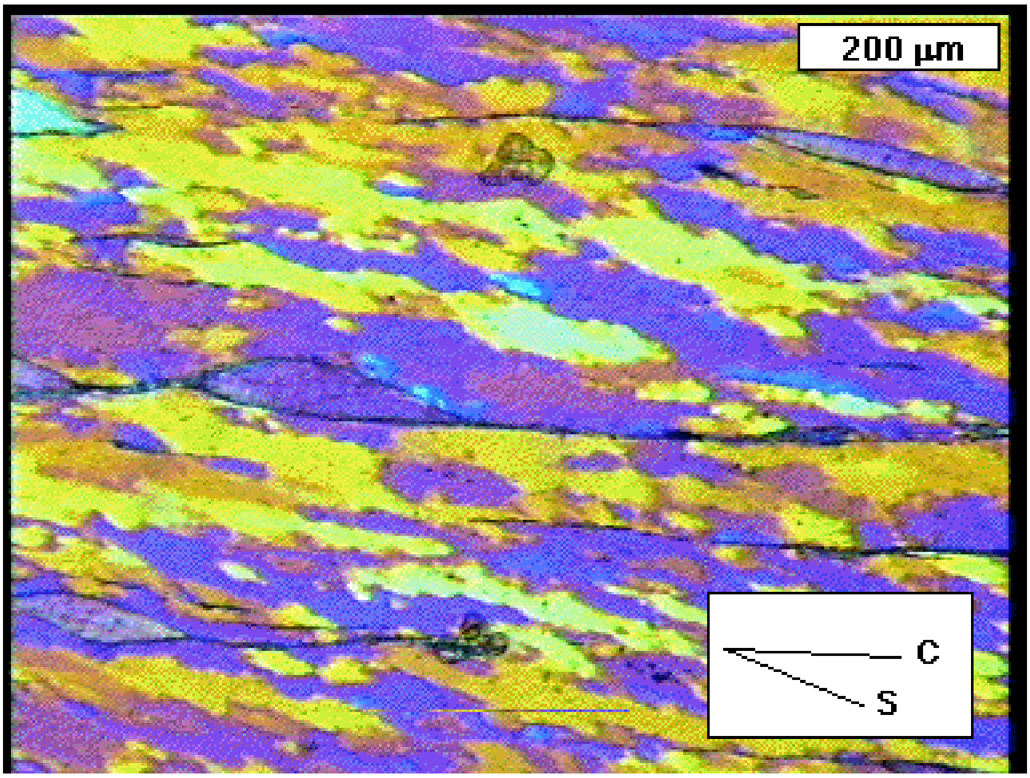
S-C fabric (Berthé *et al.* 1979, type I) often good shear sense indicator. Develops early in shear zone formation. C' (and C") are often late structures and may develop due to shear zone parallel shortening or stretching. Note: also look outside shear zone for this, since such shortening/stretching must also occur there (stress & strain rate compatibility)

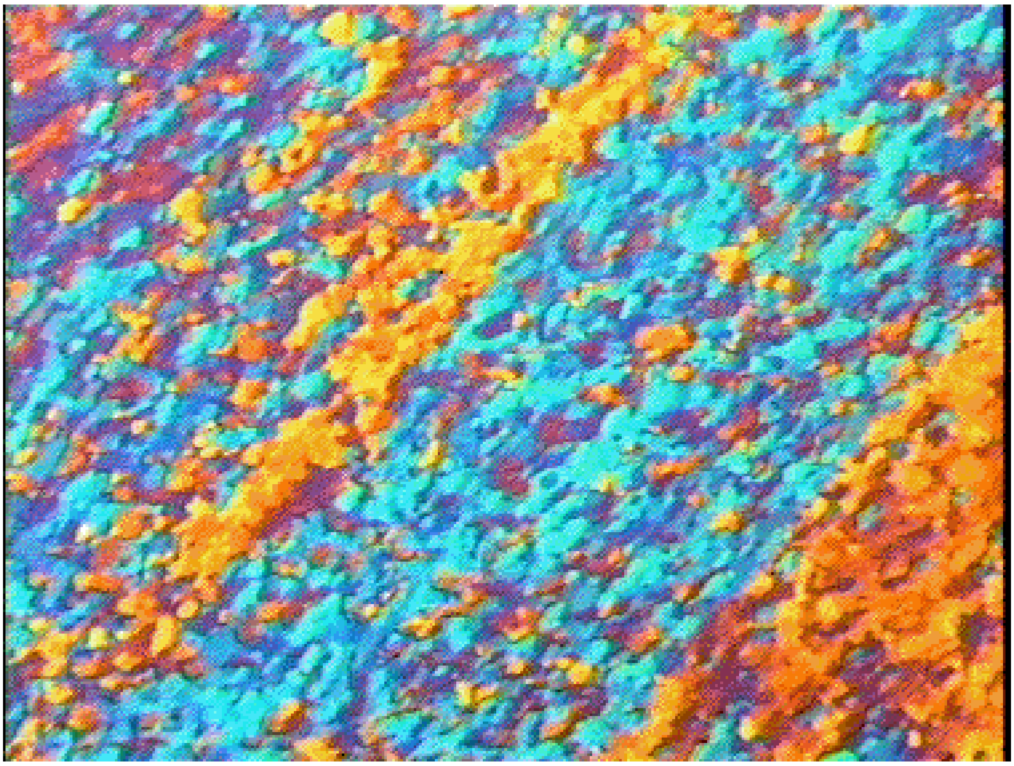
Oblique (grain shape) foliation mostly in rocks with one dominant mineral (e.g. micaceous quartzite). Angle <45º with flow plane. Combination of:

- instantaneous stretching in 45º direction (ISA)
- rotation towards flow plane
- recrystallisation

Oblique foliation + mica fish: **type II S-C fabric** of Lister & Snoke (1984).

- S = mica-fish & grain shape foliation oblique to flow plane (SZB)
- C = micaceous trails from fish parallel to SZB





Domainal fabrics: different areas within rock that display contrasts in grain size, grain shape foliation, crystallographic preferred orientation or some other microstructure

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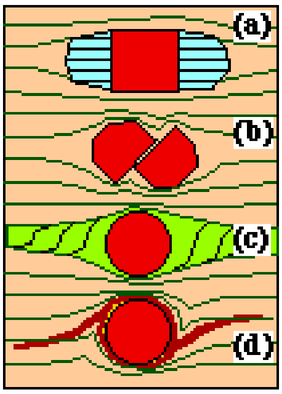
Porphyroclasts

(semi-) rigid objects cause local disturbance of stress field:

- higher differential stress inside object
- highest differential stress & pressure on 2 sides of object
- lowest differential stress & pressure on 2 other sides of object (pressure shadow)



Range of possible results in object-matrix system:

(a) loss of cohesion with extensional failure

- between object and matrix: pressure fringes
- within object: boudinage

(b) loss of cohesion with shear failure
(c) no loss of cohesion; deflection of deformation around lens including pressure shadow (strain dependent rheology, anisotropy / micas)

- in simple shear no or little rotation of object

(d) no loss of cohesion; flow of matrix around object.

in simple shear rotation of object

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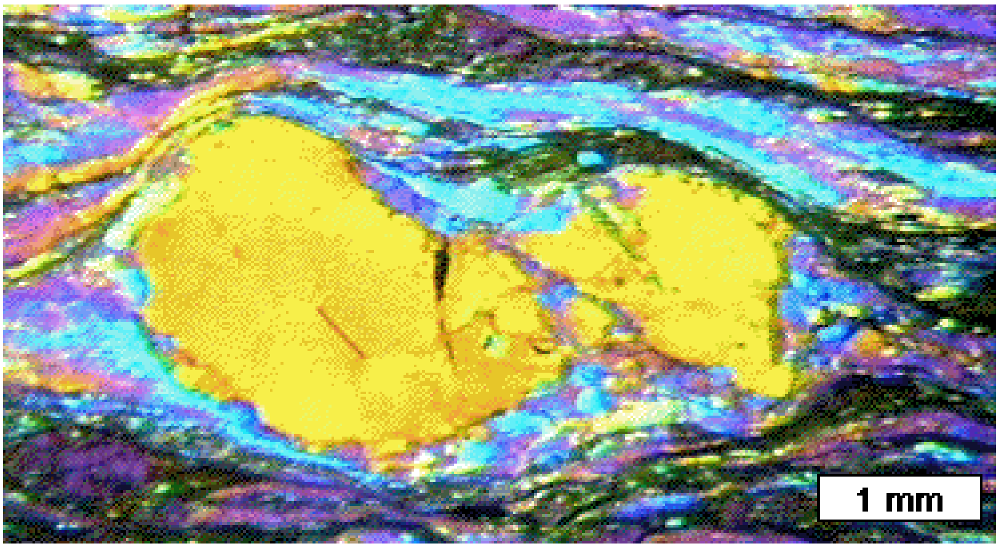
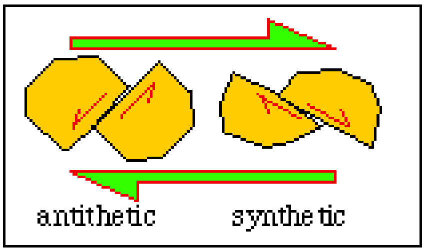
pressure shadows & fringes, very useful, see lecture 5.b

Fractured objects & tiling



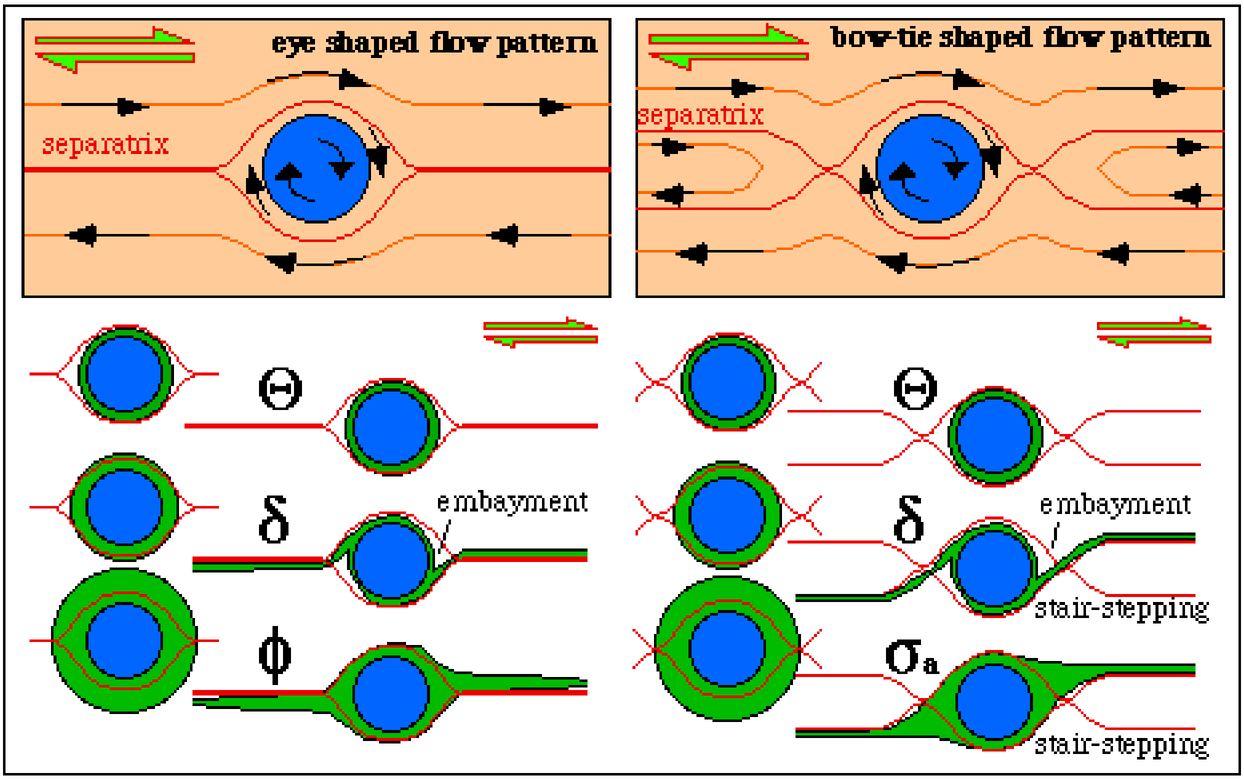


Fractured objects: antithetic and synthetic fractures (unreliable shear sense indicator). Fracture orientation depends on relative orientations of:

- shape of object
- deformation
- crystallography

Winged objects / mantled porphyroclasts. Porphyroclasts (typically feldspars) can have fine-grained mantles. The mantle forms by recrystallisation of the object rim, possibly with mixing in of matrix material (by grain boundary sliding and diffusion).

-> Mantle is **not the same** as pressure shadow or pressure fringe



With high strain, mantles can get stretched to form wings. Flow field and amount of mantle material determine geometry of mantled porphyroclasts.
Two basic flow fields, defined by shape of separatrix (planes that separate distinct flow fields)

- eye shape flow pattern:
  - one field with closed flow loops around rotating object
  - two fields where material flows past object
- bow-tie or double-bulge flow pattern:
  - one field with closed flow loops around rotating object
  - two fields where material flows past object
  - two fields where flow lines turn back from object

Θ-objects (theta): mantle completely enclosed by separatrix; cannot flow away from object

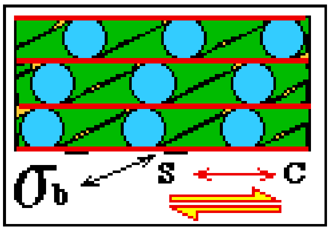
δ-objects (delta): mantle is partly outside of separatrix: part remains close to object, part flows away in long thin wings with **embayments**

ϕ-objects (phi): long wings, but no embayments; mantle extended outside of separatrix; orthorhombic symmetry

σa-objects (sigma): long wings, but no embayments; mantle extended outside of separatrix; monoclinic symmetry. σ-objects should not be confused with pressure shadows.

stair-stepping: the wings on either side of the object are parallel, but do not lie in the same plane. Upward step is in shear direction. Only use term (no) stair stepping when wings are long and parallel.

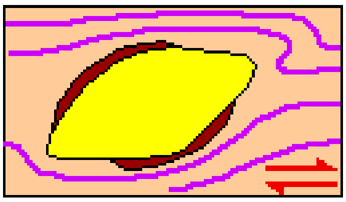
complex objects: objects with more than one pair of wings.



σ**b**-objects (sigma): mantled porphyroclasts in S-C fabric.

Quarter structures

Monoclinic symmetry of structures at porphyroclasts without mantles:



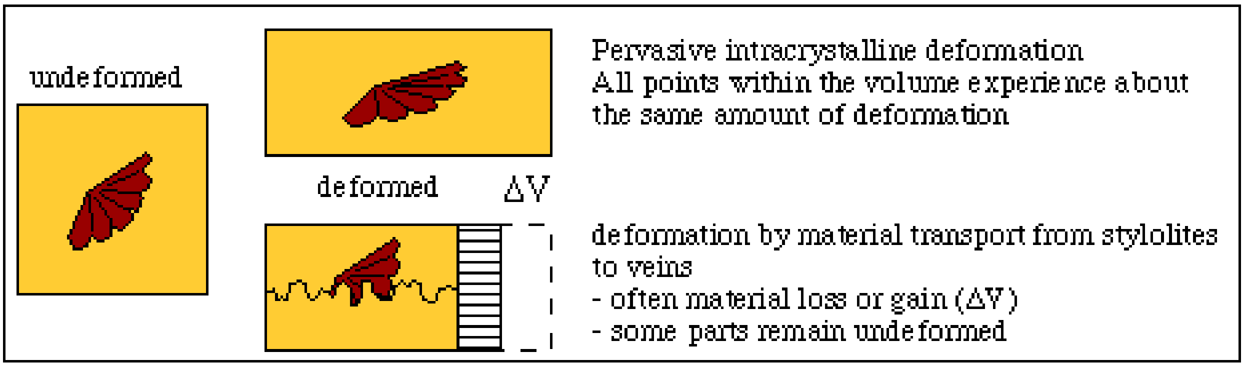
- quarter folds
- quarter mats (strain caps)
- asymmetric myrmekite (shape and distribution)
- V-pull apart structures

Lattice preferred orientations

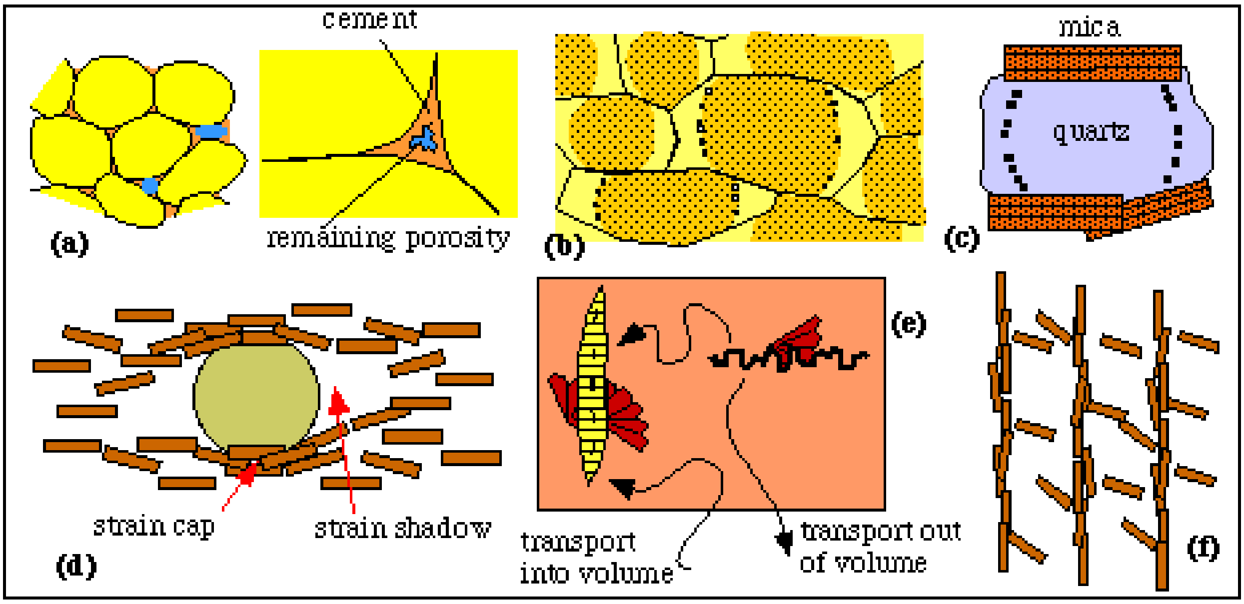
see lecture 3

Lecture 5A- Deformation by transfer of dissolved material

Introduction



Deformation can be achieved by removing material from some sites and bringing it to other sites. At length scales below the transport scale, there are sites of volume increase and volume decrease, whereas other sites remain undeformed.



Several (micro-) structures resulting from material transport due to applied stresses:

(a) Compaction of a porous rock with material dissolving at grain contacts and precipitating as cement in pores.

(b) Preferential dissolution at grain contacts that are normal to compression and reprecipitation at grain contacts that are normal to extension leads to deformation. Original grain shapes can often be discerned by differences in inclusion content of original grains and overgrowths and/or by dust rims.

(c) Preferred dissolution of quartz at quartz-mica contacts. A dust rim reveals the original grain shape.

(d) Localised dissolution (net material loss) at strain cap and localised precipitation (net material gain) at strain shadow or pressure shadow around a relatively rigid object or grain (e.g. pyrite, feldspar or quartz augen).

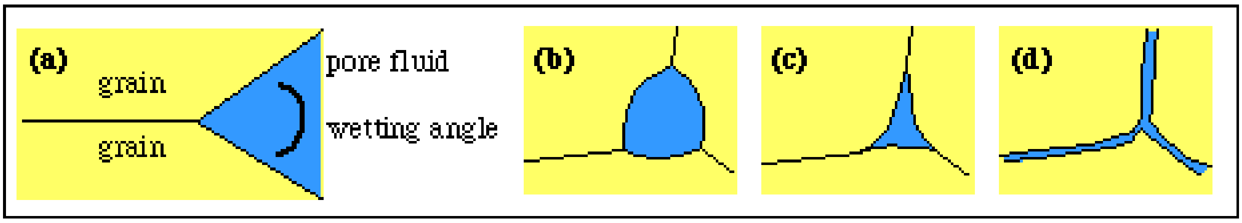
(e) Precipitation in veins and dissolution at stylolites. Material transport can be from stylolites to veins, or into / out off the system.

(f) Segregation of quartz and mica's forming domainal cleavage.

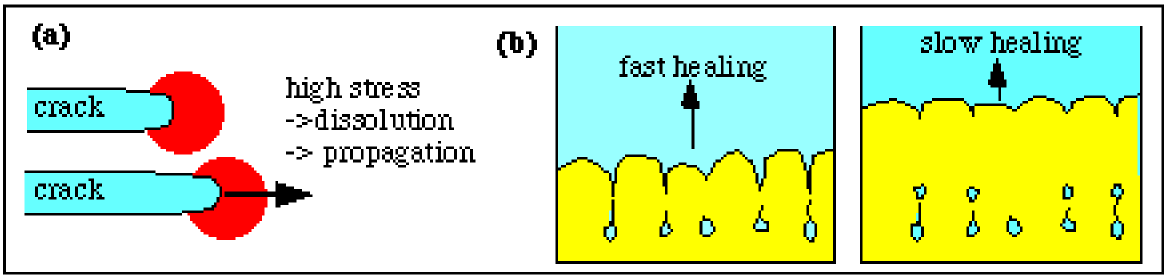
- Fluid reservoirs

A fluid is needed to transport dissolved material. Only at very high temperature can diffusional transport without a fluid be significant. Fluid can be present in a variety of different sites (reservoirs) in a rock.

1. In open cracks (> cm scale). Open fluid-filled cracks can exist at deeper levels despite the high pressure if the fluid pressure is high enough. However, open cracks greatly enhance the permeability of a rock, allowing fluids to flow and decrease the fluid pressure. There must be a dynamic equilibrium between opening of cracks (increase in permeability, decrease in fluid pressure) and closure of cracks (decrease in permeability, allowing build-up of fluid pressure).



2. Open pore space between grains. Sediments at shallow depths typically have a high porosity, which decreases with burial. At deeper levels the geometry of the pore space depends on the balance between grain-grain boundary surface energy and grain-fluid boundary surface energy: the wetting angle. The wetting angle **(a)** determines the shape of the pore space: **(b)** at a high wetting angle fluids reside in pockets where 4 grains meet; **(c)** at a medium wetting angle in tubes where 3 grain meet and **(d)** at a low (0°) wetting angle all grain boundaries are wetted. It seems that in general fluids tend to reside in pockets or tubes.



3. micro-cracks. Typical length <0.1 mm, width/length<0.01. Short-lived and dynamic structures due to rapid propagation (stress corrosion cracking), due to stress concentration at crack tip **(a)**, and rapid healing, due to surface energy effects **(b)**, possibly resulting in fluid inclusions.

---

4. Grain boundaries. The nature of grain boundaries is very important, since fluids here actually come in contact with all grains. Two general models for grain boundaries:

(a) **Thin film model**:

- The grain-contacts are completely wetted by a thin (<2 nm) fluid film
- fluid can support shear stresses
- fluid is not "free"

Thin fluid films have been observed at low normal stress, but seem to get squeezed out between 0.1 and 20 MPa. Wetting angles >0° also suggest that the thin film is probably not the correct model for most mineral aggregates.

(b) **Island-and-channel model**:

- grain-grain contacts (islands)
- interconnected free fluid pockets (channels)

In the island-and-channel model there is a stable, but dynamic, structure of grain-grain contacts that support the stress and a fluid in the channels. As islands and channels constantly migrate, the fluid can access the whole grain surface over time.

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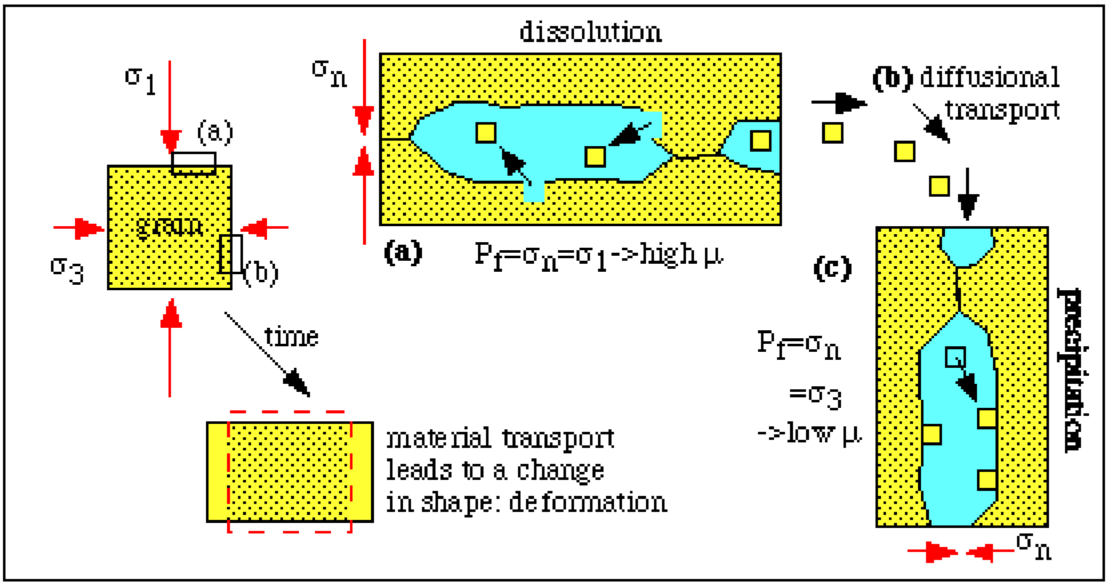
5. Inside the crystal, incorporated in the lattice (only a small amount) and in fluid inclusions.

Dissolution precipitation creep



Dissolution-precipitation creep is a deformation mechanism that involves three serial steps. The slowest of these three steps is the rate controlling step.

(a) Dissolution reaction at (relatively) high normal stress grain boundaries

(b) Diffusional transport along chemical potential (μ) gradient in grain boundary fluid

(c) Precipitation reaction at (relatively) low normal stress grain boundaries.

DP creep is the dominant ductile deformation mechanism at low temperatures in wet rocks (<= greenschist facies), where other mechanisms, such as dislocation creep are slow. Provided there is a suitable fluid, it may also be important at higher temperatures.

- Driving force

Diffusional transport and the interfacial reactions are driven by a stress induced chemical potential differences along the grain boundaries (->diffusion) and across the interfaces (->reaction). The equilibrium chemical potential (μ) of a solid dissolved in a fluid adjacent to the surface of the solid can be described as:

- $\mu = f + P \cdot V + c\gamma/R$

(with f = Helmholtz free energy of solid, P = pressure in solid, V = molar volume of solid, c = a material constant, γ = surface energy of solid-fluid interface, R = local curvature of that interface). Grain boundaries have to transmit stresses from grain to grain. Based on this one can argue that effectively $P=\sigma_n$ (Fig. 4.5). Chemical potential is therefore higher on compressive grain boundaries ($\sigma_n=\sigma_1$) than on extensional grain boundaries ($\sigma_n=\sigma_3$). Neglecting the surface energy term, the drop in μ that drives the material transport is:

- $\Delta\mu = f+\sigma_1 V-f-\sigma_3 V = \Delta\sigma V$ ($\Delta\sigma=\sigma_1-\sigma_3$ = differential stress).

- Diffusions is rate controlling

The whole of $\Delta\mu$ is used to drive the diffusion, if precipitation and dissolution are relatively fast. The flux (J) through the GB-fluid is proportional to the concentration gradient along the grain boundary, which is proportional to $\Delta\mu$ and inversely proportional to the grain size (g):

- $J \propto 1/g \Leftrightarrow J \propto \Delta\sigma/g$

The flux (F) has to go through an area proportioanl to the cross-sectional area of the grain boundaries, which is proportional to the grain size:

- $F \propto Jg \Leftrightarrow F \propto \Delta\sigma$

The dissolved solid arriving on the extensional grain boundary adds a layer of solid to it of width w:

- $w \propto F/g^2 \Leftrightarrow w \propto \Delta\sigma/g^2$

Extension rate (E) is:

- $dg/dt = w/g \Leftrightarrow E \propto \Delta\sigma/g^3$

When diffusion is rate controlling, the strain rate is proportional to the differential stress (linear or Newtonian viscous) and inversely proportional to the cube of the grain size.

-Reaction is rate controlling

The whole of $\Delta\mu$ is used to drive the interfacial reactions, if precipitation and dissolution are relatively slow compared to diffusional transport. The rate (w) of precipitation and dissolution are (normally) proportional to the chemical potential difference across the interface:

- $v \propto \Delta\mu \Leftrightarrow v \propto \Delta\sigma$

The extenion rate is given by the growth rate divided by the grain size:

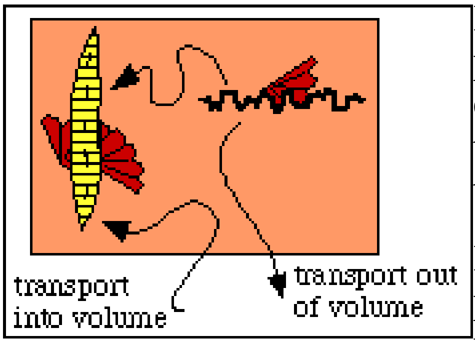
- $E = dg/dt = w/g \Leftrightarrow E \propto \Delta\sigma/g$

When interfacial reactions are rate controlling, the strain rate is again proportional to the differential stress (linear or Newtonian viscous) and inversely proportional to the grain size. Pressure solution creep is favoured by a small grain size, and the grain size must be especially small for reaction controlled pressure solution creep.

- Material transfer on larger length scales (veins, stylolites, around objects)

Deformation induced material transfer can also occur on length scales larger than one grain. Since the 'effective grain size' would then be much larger, it is clear that the rate of such transfer to produce deformation is low ($1/g$ or $1/g^3$) compared to grain scale pressure solution creep. As a deformation mechanism, long distance transport is not very important, but it is as a significant process that produces structures in rocks, such as veins, stylolites and cleavages.

Material transfer on large length scales (>>g) occurs when some areas within a rock volume experience a net volume loss and/or other areas a net volume gain. In other words a heterogeneous distribution of precipitation and dissolution.



If dissolution consistently outweighs precipitation at a plane, this plane is a site of net volume loss: a stylolite. Stylolites are often oriented normal to the maximum compression direction. The material that is removed can be carried away by diffusion and/or flow of a fluid through the rock.

If precipitation consistently outweighs dissolution at a plane, this plane is a site of net volume gain: a vein. Veins are typically oriented normal to the minimum compression direction, and are then usually called tension gashes. The material that is added can be carried in by diffusion and/or flow of a fluid through the rock.

- Why & where localised precipitation?

a) not controlled by dissolution precipitation creep.

- Cracks
- relatively rigid objects
- layering

Primary mechanical heterogeneities provide heterogeneities in stress state and pressure and preferred sites for precipitation

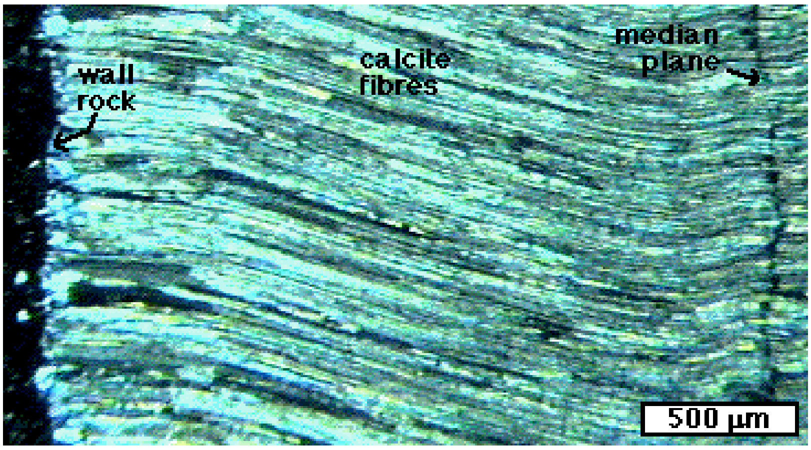
b) localisation of dissolution and/or precipitation coupled to dissolution precipitation creep: development of regular alterations of dissolution & precipitation.

- cleavage
- gneissic layering
- migmatitic layering

Continue to lecture 5.b: (Micro) structures in veins

Veins

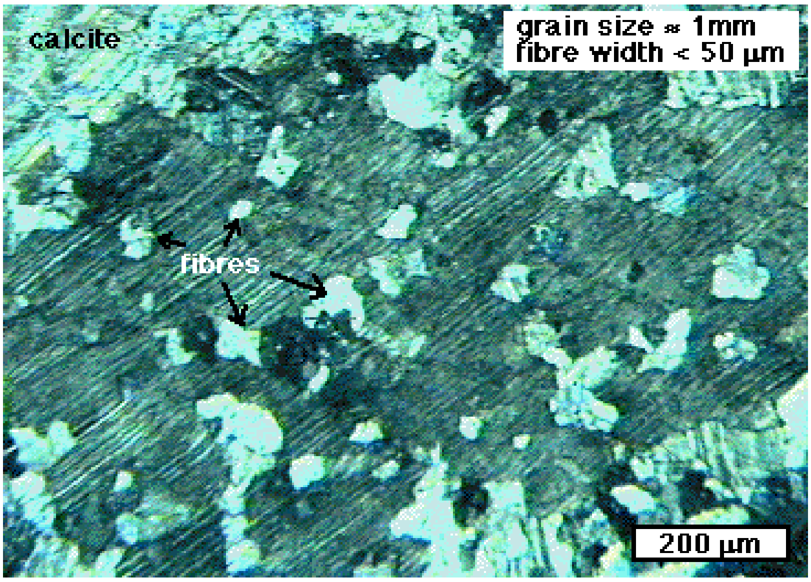
- Terms relating to the shape of crystals in veins



Fibrous:

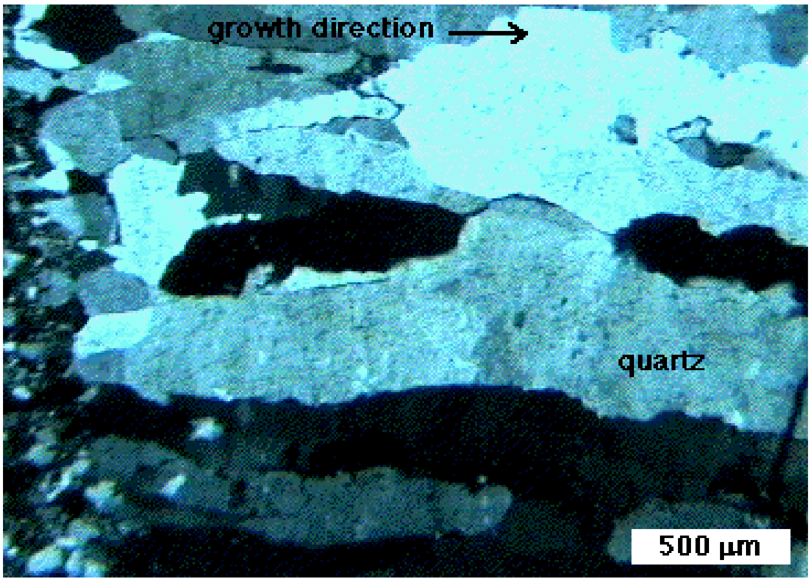
- High to extreme length/width ratio of grains (>10 ... >100)
- Fibrous shape not determined by crystal habit
- Fibrous shape independent of crystallographic orientation of grains
- Shape of all grains identical
- All fibres parallel
- No nucleation during growth

(Antitaxial calcite vein in carbonaceous shales, Arkaroola, South Australia)



NB. A fibrous texture can be formed by fibrous sub-grains or twins, while the true grains may not really be fibrous. Here you see a section perpendicular to the fibres in an antitaxial vein. One grain covers most of the image. The fibres are much smaller and are defined by sub-grain and possibly twin-boundaries.

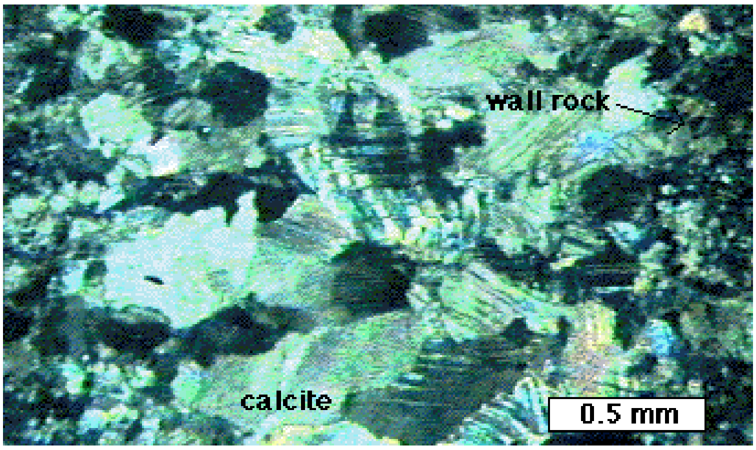
(Antitaxial calcite vein in carbonaceous shales, Arkaroola, South Australia)



Elongate blocky:

- Low to high length/width ratio of grains (<10)
- Elongate shape not determined by crystal habit
- Fibrous shape often related to crystallographic orientation of grains
- Not all grains have identical shape
- Long axes of grains in approximately same direction
- No nucleation during growth

(Syntaxial/asymmetric quartz vein from Cape Liptrap, Victoria, Australia)

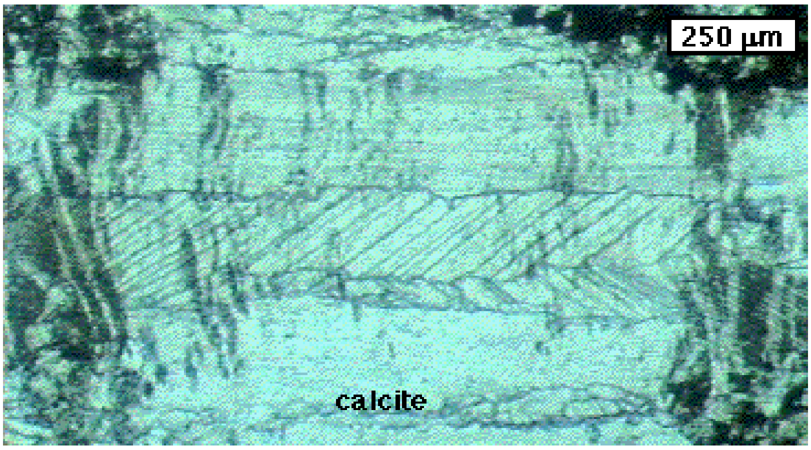


Blocky:

None of the specific characteristics of fibrous or elongate blocky textures, in particular:

- Often continuous nucleation
- No elongate shape and/or shape preferred orientation of crystals

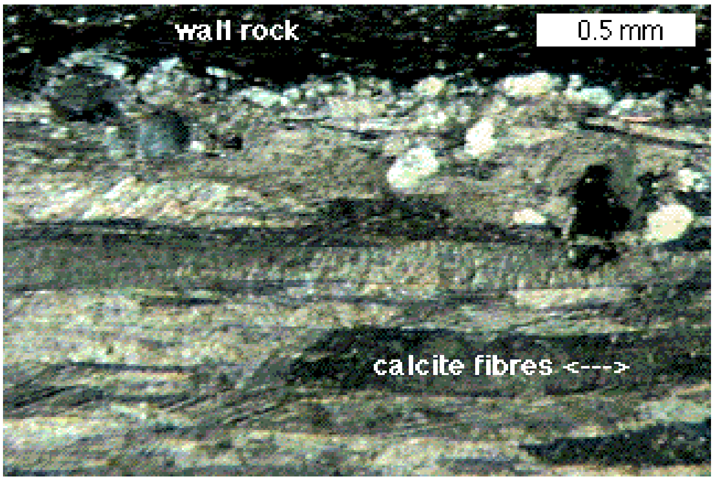
(Calcite vein in carbonaceous shales, Arkaroola, South Australia)



Stretched:

- Elongate crystals
- Parts of pre-existing grain at both ends of crystals
- Often "radiator" structures and/or jogs on grain boundaries

(Calcite vein in carbonaceous silt stone and shales, Arkaroola, South Australia)

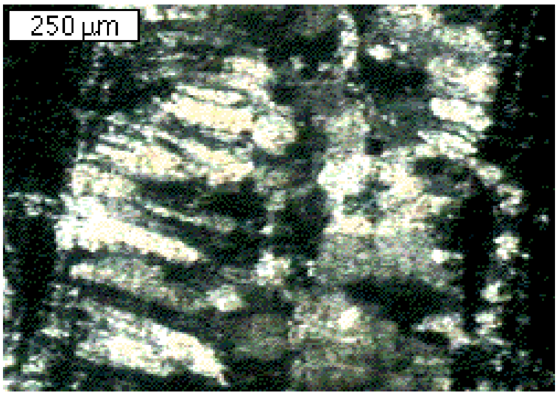


Slicken-fibres:

- Fibrous or elongate blocky crystals
- Long axis of crystals at low angle or parallel to vein wall

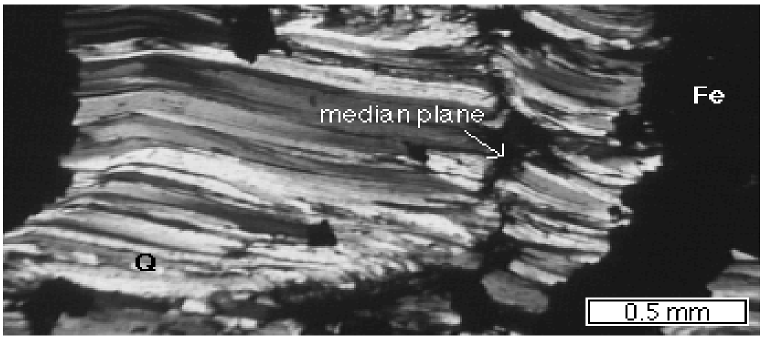
(Calcite vein in carbonaceous shales, Arkaroola, South Australia)

- Terms relating to site(s) of precipitation during growth of a vein



Syntaxial veins:

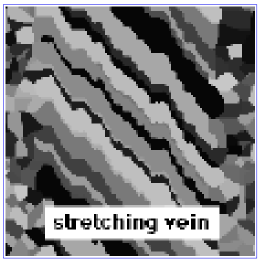
- Growth persistantly occurs at the same plane
- Growth occurs in the middle of the vein
- Growth often commences by syntaxial (crystallographic sense) overgrowth of wall rock grains
- Often elongate blocky
  - Oldest precipitate is on vein - wall rock contact; youngest on median plane
  - Individual crystals do not extend across median plane



(Asymmetric antitaxial quartz vein from BIFs in Hammersley Ranges, W.Australia)

Antitaxial veins:

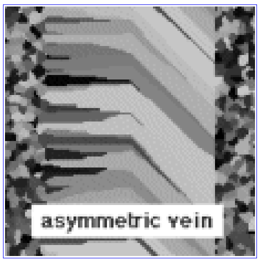
- Growth persistantly occurs at the same planes
- Growth occurs on the two vein - wall rock contact surfaces
- Mineral(s) growing in the vein are often absent in, or a minor constituent of the wall rock
- Often fibrous
  - Youngest precipitate is on vein - wall rock contact; oldest on median plane
  - Individual crystals extend across median plane



Ataxial or **stretching veins:**

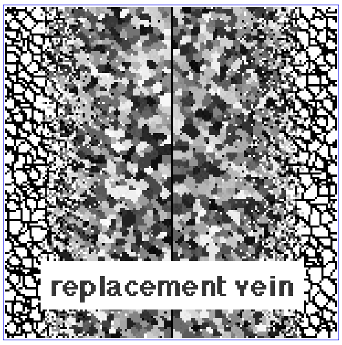
- Growth occurs at various sites (cracks) over time
- Mineral(s) growing in the vein are often major constituent of the wall rock
- Stretched crystalls
- -> No consistent variation from young to old precipitate
- -> No median plane
- -> Individual crystals extend from wall to wall of the vein

Cracks can occur inside the vein only or they can occur randomly (but usually parallel). In the second case, the vein contains many slivers of wall-rock.



Asymmetric veins:

- Growth commences by ataxial growth (usually, but can be syn/antitaxial)
- One side of the vein becomes preferred growth plane
- Often elongate blocky
- -> Veins are asymmetric



Replacement veins:

- Vein precipitate is not in newly created space, but replaces pre-existing minerals.
- Usually vague edges
- Inclusions of pre-existing grains often remain
- Crystal shape often blocky or determined in shape and size by pre-existing texture

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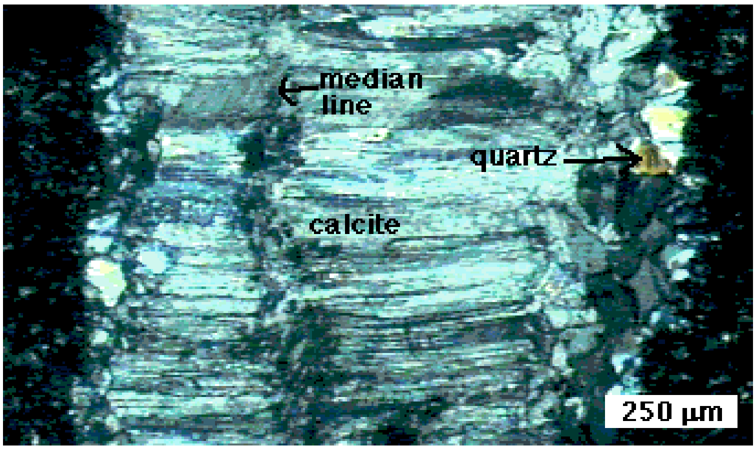
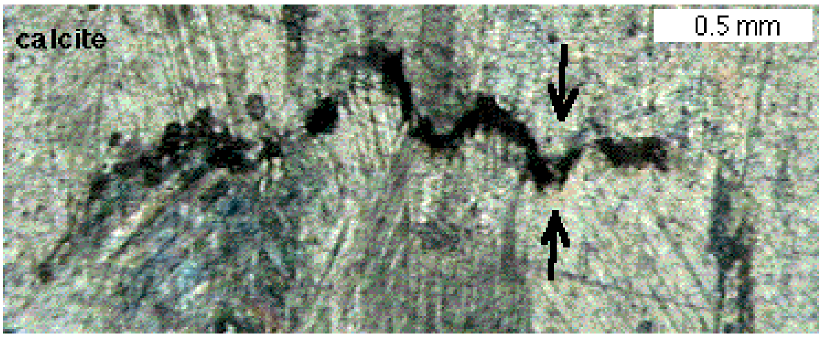
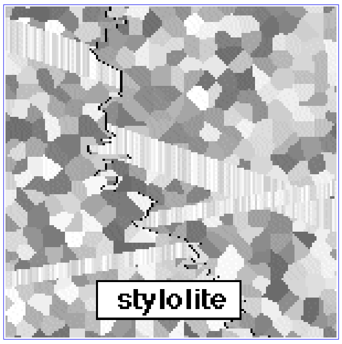


Composite veins:

- Combination of syntaxial growth on both margins of vein and syntaxial growth in centre of vein.
- Usually different minerals forming syntaxial and antitaxial parts

(Calcite + quartz vein in carbonaceous shales from Arkaroola, South Australia)





(Stylolite in calcite vein in carbonaceous shales from Arkaroola, South Australia)

Stylolites:

Stylolites are in a way the opposite of veins (hence the term 'anti-crack' which is sometimes used).

- Continuous / repetative dissolution on a plane
- Accumulation of insoluble material (often dark/opaque) on stylolite
- Saw-teeth shape develops, due to differences in dissolution rate on either side of stylolite
- Saw-teeth indicate the direction of shortening

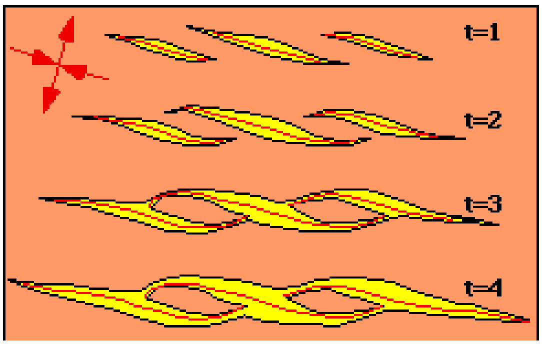
- Tracking of opening trajectory

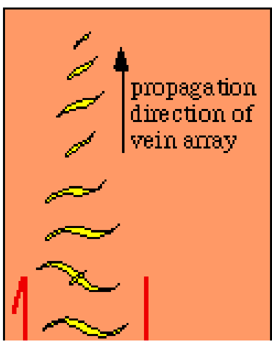
The opening trajectory is the path that two, originally adjacent, points on the oposite vein walls travelled relatively to each other as the vein grew. Fibres & elongate blocky crystals often track the opening trajectory, but not always completely (=partial tracking).

Ghost fibres may sometimes give a more reliable indication of the opening trajectory than normal fibres. Ghost fibres are trails of a different mineral growing off a specific point (grain) on the wall rock.

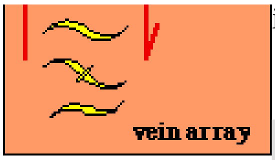
- Veins and structural analysis

The wide variety of internal structures of veins, vein shapes and vein arrangements make veins useful structures for structural analysis. Quite often the elongate blocky or fibrous crystals in a vein allow us to determine the whole history of the formation of a vein, giving insight in the deformation history of its host rock. The micro-structures should of course be correctly interpreted (syntaxial or antitatxial, partial or complete tracking, etc.).

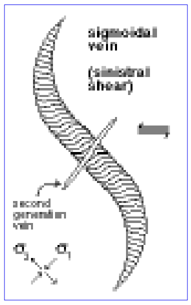




Veins also often form in arrays. The left image shows a group of veins that originally formed at a small angle with the horizontal. Interaction between the veins caused them to merge into one horizontal vein with wall rock inclusions. The right image shows a set of sigmoidal veins. The veins did not form all at the same time and are in different stages of development (see film below). Sigmoidal vein arrays are often useful kinematic



indicators.



- Sigmoidal veins

Opening (widening) of a vein is in maximum instantaneous stretching direction

- opening trajectory records kinematics of deformation

Propagation of vein-tips parallel to maximum instantaneous shortening direction

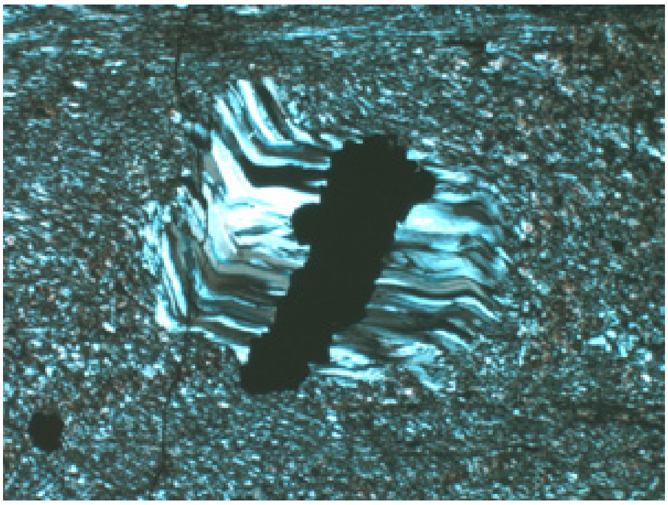
Opening of vein parallel to maximum instantaneous extension direction

Vein rotates when deformation is non-coaxial

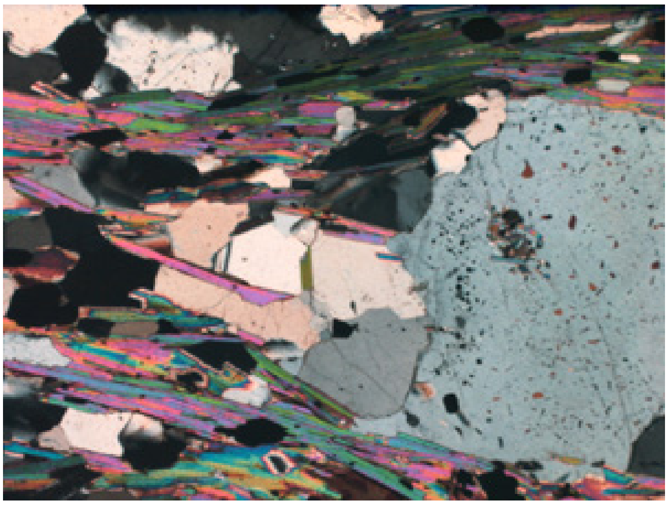
- Sigmoidal veins form

Strain/pressure fringes & shadows around rigid objects

A rigid object (e.g. pyrite crystal) disturbs the stress and strain field around it during deformation. On the sides of the object normal to maximum compression, differential stress and pressure are highest (high strain areas). On the sides of the object normal to minimum compression, differential stress and pressure are lowest (low strain areas). Difference in pressure can lead to material transport from strain cap to pressure shadow or pressure fringe (alternatively called strain shadow and strain fringe).

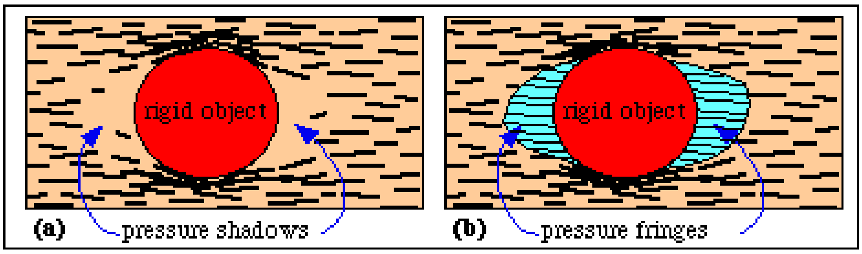


Pressure fringe of fibrous quartz around a concretion of iron ore in a BIF-chert from the Hamersley ore province, Pilbara, West Australia.
Width of view 2.3 mm, crossed polars.



Quartz + mica pressure shadow adjacent to a quartz porphyroclast (on right, grey grain with inclusions) in a quartz-mica schist from Nooldoonooldoona Waterhole, S.W. Mount Painter Inlier, Arkaroola, South Australia. Width of view 3.2 mm, crossed polars. Note the sharp boundary of the pressure fringe, in contrast to the vague boundary of the pressure shadow

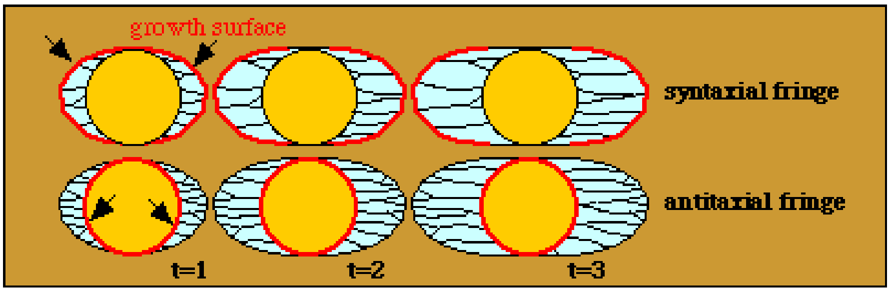
- Fringes versus **shadows**



distributed precipitation in low pressure area:	localised precipitation in low pressure area:
pressure shadow • usually blocky texture • non-distinct boundary of pressure shadow • similar to replacement veins	**pressure fringe** • usually fibrous or elongate blocky texture • sharp edge of pressure fringe • similar to syntaxial/antitaxial/composite veins

NOTE: later recrystallisation may produce a blocky texture in a pressure fringe, making it look like a pressure shadow.

- Syntaxial versus antitaxial fringes



Syntaxial fringe: • precipitation is on **outside** of pressure fringe: **between fringe & wall rock** • precipitate can be same mineral as core object with crystallographic continuity between object and fringe • relatively uncommon	**Antitaxial fringe:** • precipitation is on **inside** of pressure fringe: **between object & fringe** • precipitate usually different mineral as core object • relatively common (typically pyrite with quartz and/or calcite fringe)

Notice that at the syn-/antitaxial terminology for veins and fringes seems inconsistent. Reason:

- in veins, the wall rock is reference material
  - in syntaxial veins crystals grow syntaxially from wall rock grains
  - in antitaxial veins crystals grow antitaxially towards wall rock
- in fringes, the core object is reference material
  - in syntaxial fringes crystals grow syntaxially from core object
  - in antitaxial fringes crystals grow antitaxially towards core object

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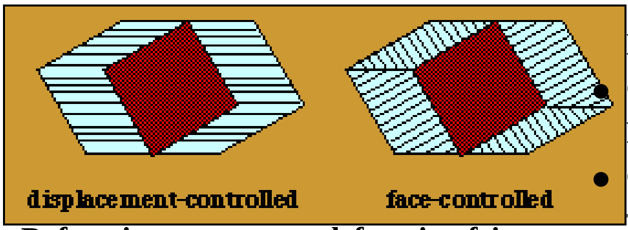
- Displacement versus face-controlled growth



- **Displacement-controlled** growth:
  Growth direction of fringe crystals (fibres) = opening direction
- **Face-controlled** growth:
  Growth direction of fringe crystals (fibres) = normal to object surface

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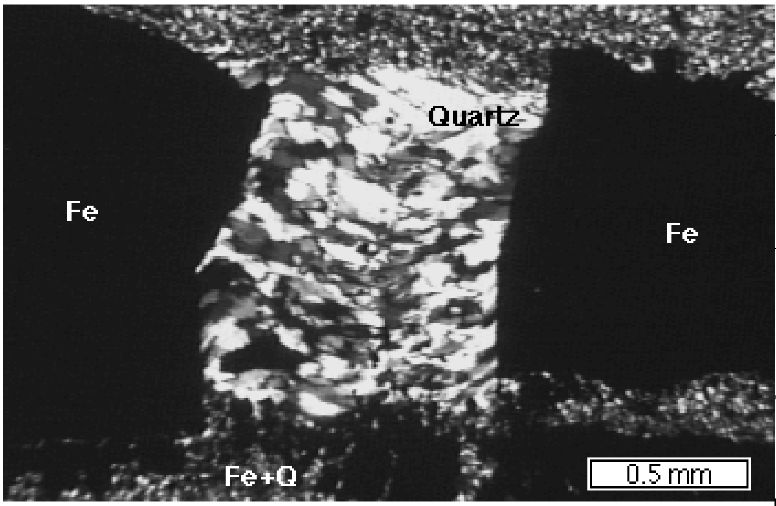
- Deforming versus non-deforming fringes

The fringe mineral can be very strong compared to the surrounding material and behave as rigid material. The texture in the fringes is preserved. The fringe gets deformed if the fringe mineral is not effectively rigid.

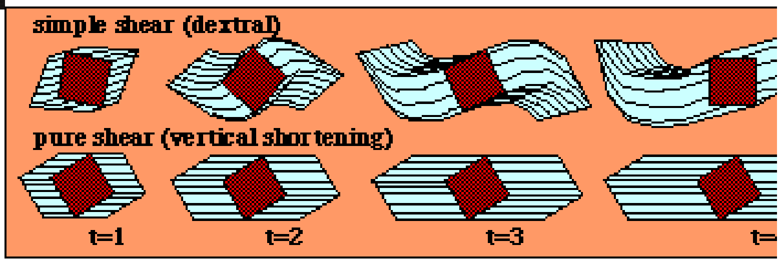


- Pressure shadows/fringes in boudin necks

Pressure shadows and fringes also occur in boudin-necks of competent layers or in between parts of broken rigid (but brittle) crystals.

(Quartz fringe in broken lump of iron ore in BIF from Hammersley Ranges, Western Australia)

- Pressure shadows/fringes and structural analysis



As with veins, the shape of pressure shadows / fringes and the internal texture of fringes often provide excellent information about the kinetics of deformation during their formation:

- degree of non-coaxiality of deformation
- amount of deformation (finite strain)
- possible changes in deformation kinetics

The crack-seal mechanism

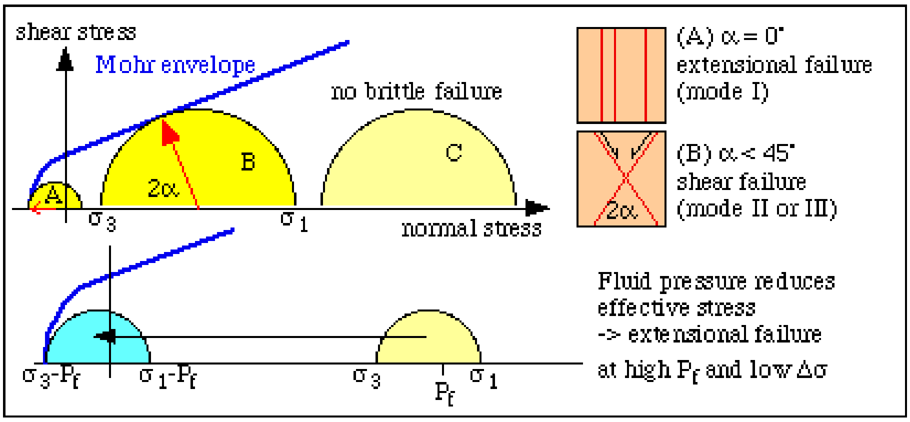
The crack-seal mechanism (Ramsay 1980) is the favoured mechanism for about all veins with elongate crystals. In this model growth occurs in many repeated small increments: crack-seal events:

- Crack event -> opening of narrow open crack, filled with fluid
- Seal event -> Precipitation fills (=seals) the crack again

Most telling microstructural indicators of crack-seal mechanism are regularly spaced trails of small inclusions (typically small micas or pieces of wall rock or fluid inclusions). Opening per crack event is generally in the order of 10 µm.

Elongate blocky and stretching textures are very well explained by, and often show evidence of crack-seal growth (inclusions, radiator structures)

- Crack-seal mechanism, pressure and fluid flow



The crack-seal cycle involves the buildup of fluid pressure to enable fracturing (Crack). Then increased permeability allows fluid flow and material transport (Seal) and the fluid pressure drops.

- Presence of cracks -> fluid can flow through crack network
- Presence of cracks -> brittle failure (often extensional)
- Extensional failure -> high fluid pressure & low differential stress

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- Fibrous textures and the crack-seal mechanism: some questions

How does material get to vein?

- percolating fluid: precipating in and clogging of cracks
- diffusional transport: local material

Which textures develop ?

- growth of crystals into open cracks is crystallographically determined, resulting in elongate blocky textures and a preferred crystallographic orientation
- to get fibrous texture:
  - isotropic growth (special conditions, sub-grains or twins)
  - growth is not in open crack, but on wall rock - fibre tip contact **(*)**

Why often tracking of opening trajectory ?

- tracking capability is a function of growth anisotropy (crystallography), vein wall geometry (roughness) and crack width.
- if crack width ->0 best tracking **(*)**

How to get symmetric opening in anti-taxial vein ?

- Simultaneous or alternating failure on both sides of vein is difficult to imagine. More likely to see one side winning and get asymmetric elongate blocky vein
- Diffusional transport to and precipitation on surface of vein gives symmetric antitaxial vein **(*)**

(*) These observations suggest that the crack seal mechanism is not the only mechanism: it best explains the formation of syntaxial or asymmetric elongate blocky veins. Fibrous antitaxial veins may form without repeated cracking and sealing, but by continuous growth on the surface of the vein, with diffusional transport of material to the vein.

Lab 1a-Deformation Mechanisms

VIEPS/Mainz Microstructure Course

Further Reading:

An Outline of Structural Geology, 1976. Hobbs, Means & Williams p 73-104

Crystalline Plasticity and Solid State Flow in Metamorphic Rocks, 1976 Nicholas & Poirier p 52-121

Creep of Crystals, 1985 Poirier p 38-63

***Microtectonics*, 1996, C. W. Passchier & R.A.J. Trouw, Springer-Verlag, Berlin.**

1) Computer simulations and animations of deformation mechanisms.

The first part of the lab consists of a series of computer animations of various small scale deformation mechanisms.

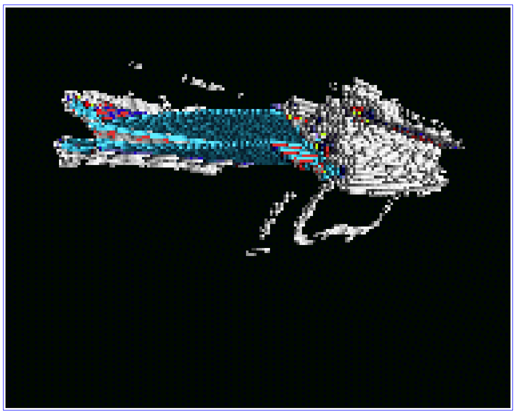
To view the images in this course as a movie, click on the right arrow at the bottom left of the picture (or fast forward and reverse with the arrows on the lower right hand side).

A) Molecular Dynamics Simulations.

These are numerical simulations where the interactions between atoms in a crystal are calculated for systems typically with 100x100x100 atoms. These allow the investigation of VERY small scale deformation processes.

In the movie below, the dislocations generated around a crack tip have been modelled numerically by a technique known as non-equilibrium molecular dynamics. In this technique the interactions between atoms are modelled, and the visualisation shows only those atoms with high energy states (ie near dislocations). The big loops that develop near the crack tip are typical of real dislocations. Further information on this study can be found in (S. J. Zhou, et al., Physical Review Letters, 78, 1997).

- If these simulations have 10 million atoms in them, how many times larger would they have to be to simulate a single 1 mm cube of quartz? (You will have to find lattice cell parameters for quartz from a minerallogy text book). Similarly these simulations run at strain rates of $10^{+8}s^{-1}$, how many orders of magnitude is this from a "geological" strain rate?



If you have access to the web and a PC or a PC emulator for the Mac, get a copy of atomdemo from http://www.ims.uconn.edu/centers/simul/progdoc/atomdemo/atomdemo.html and you will be able to run your own 2D molecular dynamics simulations.

B) Dislocation Dynamics Simulations

The following links are to dislocation dynamics simulations calculated by Benoit Devincre and Ladislas Kubin at the Laboratoire d'Etude des Microstructures (CNRS/ONERA) and show a variety of dislocation motions and interactions.

- Dislocation Frank-Read source.
- Dynamics of two interacting Frank-Read sources, repelling and attracting.
- Dislocation dipole.
- Dislocation annihilation by cross-slip.
- Dislocation double cross-slip.
- Dislocation-dislocation reaction.
- Dislocation "forest" interactions.
- Dislocation 3D dynamics.

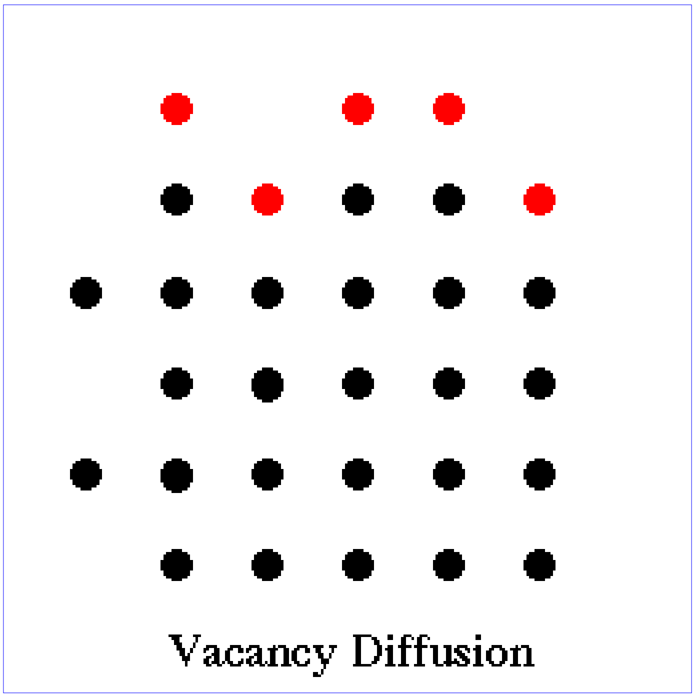
- Give a brief description of each simulation.

Graphical Animations of Processes

- Explain how each process below leads to the straining and formation of microstructures in the crystals.

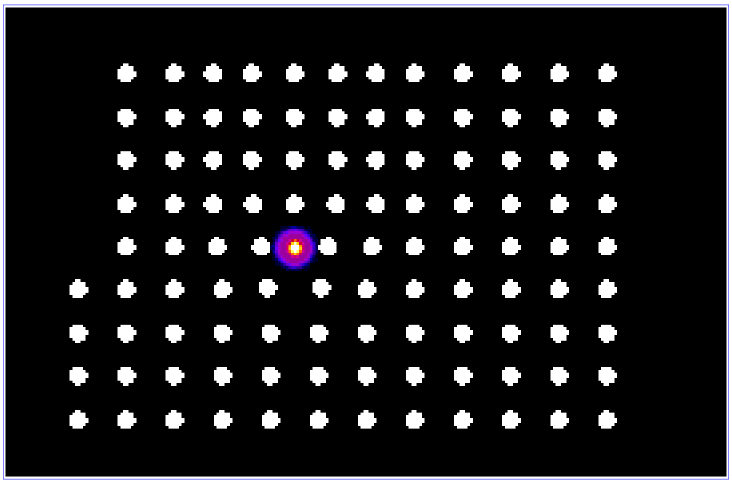
C) Vacancy migration. In this movie we see a small rectangular crystal change its shape via the motion of vacancies through the crystal. Notice how the last vacancy takes a very circuitous route through the crystal, which is in fact an under-representation of the amount of random diffusional motion that would actually take place.

- What might cause a non-random motion of vacancies in a natural crystal?



D) Edge Dislocations Motion. In these movies a single horizontal glide plane is activated by elastic strain build up in a crystal. Watch as the lattice bonds in the glide plane get stretched, and then switch one by one to a new orientation, and then once the dislocation has passed through the crystal, how this allows the further slip of the crystal on the glide plane.

- Notice how the distortion of the lattice is restricted to a small area around the tip of the extra half plane. This zone of elastic distortion (known as the dislocation core) is a fast diffusional pathway for fluid migration, and also provides the driving force for various other deformation processes
- Notice also that in this cubic symmetry crystal another perpendicular slip system may well be active at the same time, to say nothing of possible slip systems at 45 degrees to the existing one.



For both screw and edge dislocations the unit displacement of the crystal lattice is known as the Burgers vector.

F) Dislocation loops and Frank-Reed Sources of Dislocations. If you have a dislocation which forms a complete loop, the loop diameter can grow as a shear stress is applied, causing strain in the crystal. How do new dislocations form? Well one really good way of generating an endless supply of dislocations is to have a Frank-Read source, which you have already seen above, which is really just a glide plane with two sticking points on it at which a glissile dislocation sticks. The stress on the initially straight dislocation bends it out until it bends so far around it joins up with itself and forms a closed loop, which then just grows in size. The remaining pinned dislocation then starts again and generates an endless supply of free loops.

This type of source will necessarily result in a concentration of slip on just a few planes, rather than even glide throughout the body of the crystal, and this is what is seen in experimental deformation of single crystals.

G) Tilt-wall formation. This movie of ice deformation made by Chris Wilson has us looking side on on a bending crystal, and shows the initial bending of a crystal (eg the light green grain in the top-left), with the re-generation of perfect crystal by the addition of dislocations of the same sign to a developing sub-grain (tilt wall boundary). This process will convert a grain showing an undulatory extinction microstructure to one with a sub-grain microstructure.

- In the same grain a twist wall boundary forms on the left hand side. How do we know this is a twist boundary (assuming that only basal glide is active)?
- What would happen if two tilt-wall sub-grain boundaries with the same sign coalesce? What would happen if two tilt-wall sub-grain boundaries with the opposite sign coalesce?

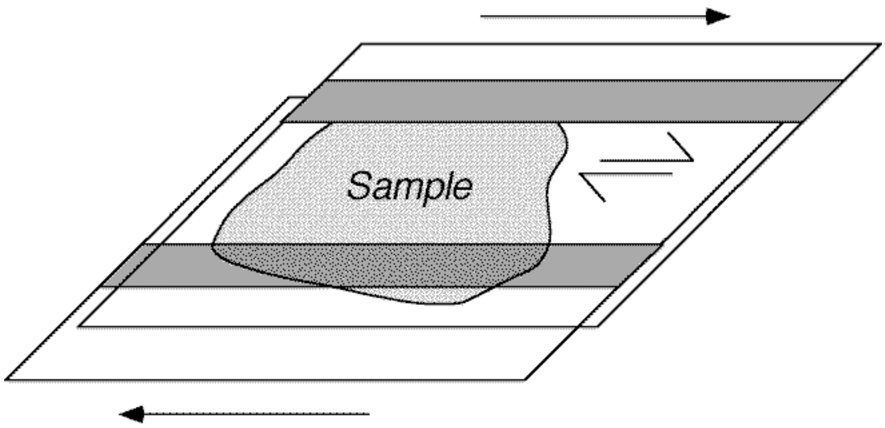
H) Twinning. In this example from Janos Urai, the limited nature of twinning is exposed: one a crystal has twinned in a certain orientation, it cannot accommodate more strain, although you do see more than one twin set is activated in this crystal. You could un-twin it by changing the stress orientation, but otherwise twinning is fixed in both the incremental amount and the total amount of strain that can be achieved. Nevertheless twinning is a very important low temperature-low strain deformation mechanisms in calcite.

- How could you distinguish a kink band from a twin in a natural crystal.

Lab 1b-Deformation Mechanisms

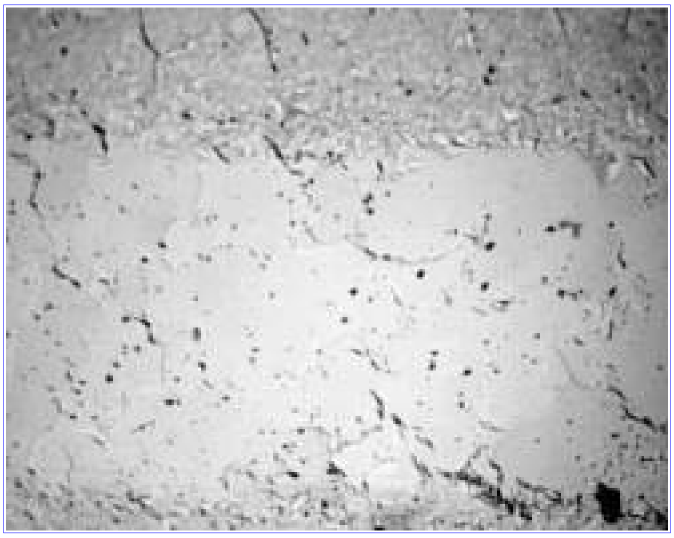
2) Mechanical experiments in analogue materials.

Real rocks are generally very hard to deform at room T & P, however by examining the behaviour of non-geological materials we can learn a lot about the mechanics of deformation and microstructure formation. We will look at four small excerpts from some experiments performed by Youngdo Park, Win Means, and Jin-Han Ree from the State University of New York at Albany, using an organic chemical called Octachloropropane (C_3Cl_8). All the experiments were performed by shearing the material between two glass plates, with thin frosted strips acting as grips as shown on the next figure...



A) Movie 01- Fracture and flow of polycrystalline OCP Fracturing and frictional sliding are often neglected deformation mechanisms in rocks that also show crystalline plasticity.

Estimate the shear strain shown in this movie, and guesstimate the amount of shearing taken up by the sliding plane about 20% up the image.



B) Movie 02 Plasticity and fracture in polycrystalline OCP

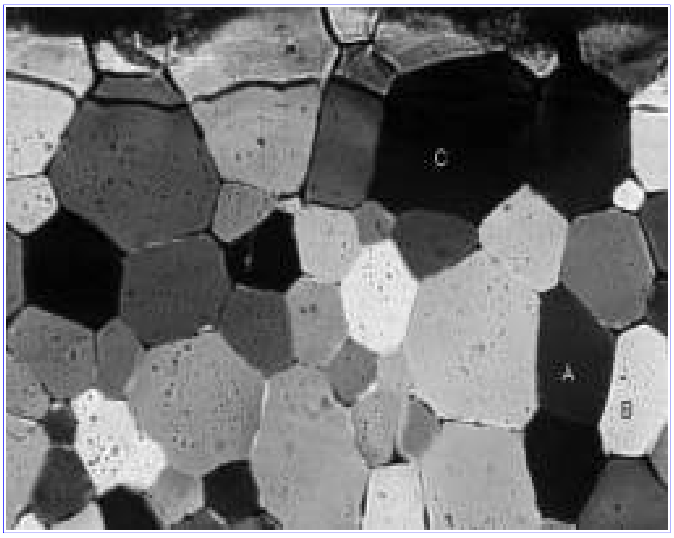
These two movies show fracturing and sliding behaviour in OCP at the same time as twinning, and at the same time as intra-crystalline plasticity. The final frame of the movie shows the microstructure in plane light, to highlight the fractures. Describe the deformation mechanisms evident in the two movies, and explain how they allow shape change in the aggregate.

- Which ones leave a microstructural signature?

C) Undulose Extinction

Play the movie below. In this movie we can see the development of undulose extinction in two grains A & B. Notice the contrast in behaviour between the two grains, with one showing very sharp variations within the grain in orientation (and hence extinction), and the other showing only gradual changes. What deformation mechanisms can you see evidence for in this movie.

- Which ones leave a microstructural signature? What intra-grain controls are there that could lead to this difference? What inter-grain controls are there? Write down your predictions for the microstructural development with continued deformation?



Movie 03 Undulose extinction in polycrystalline OCP

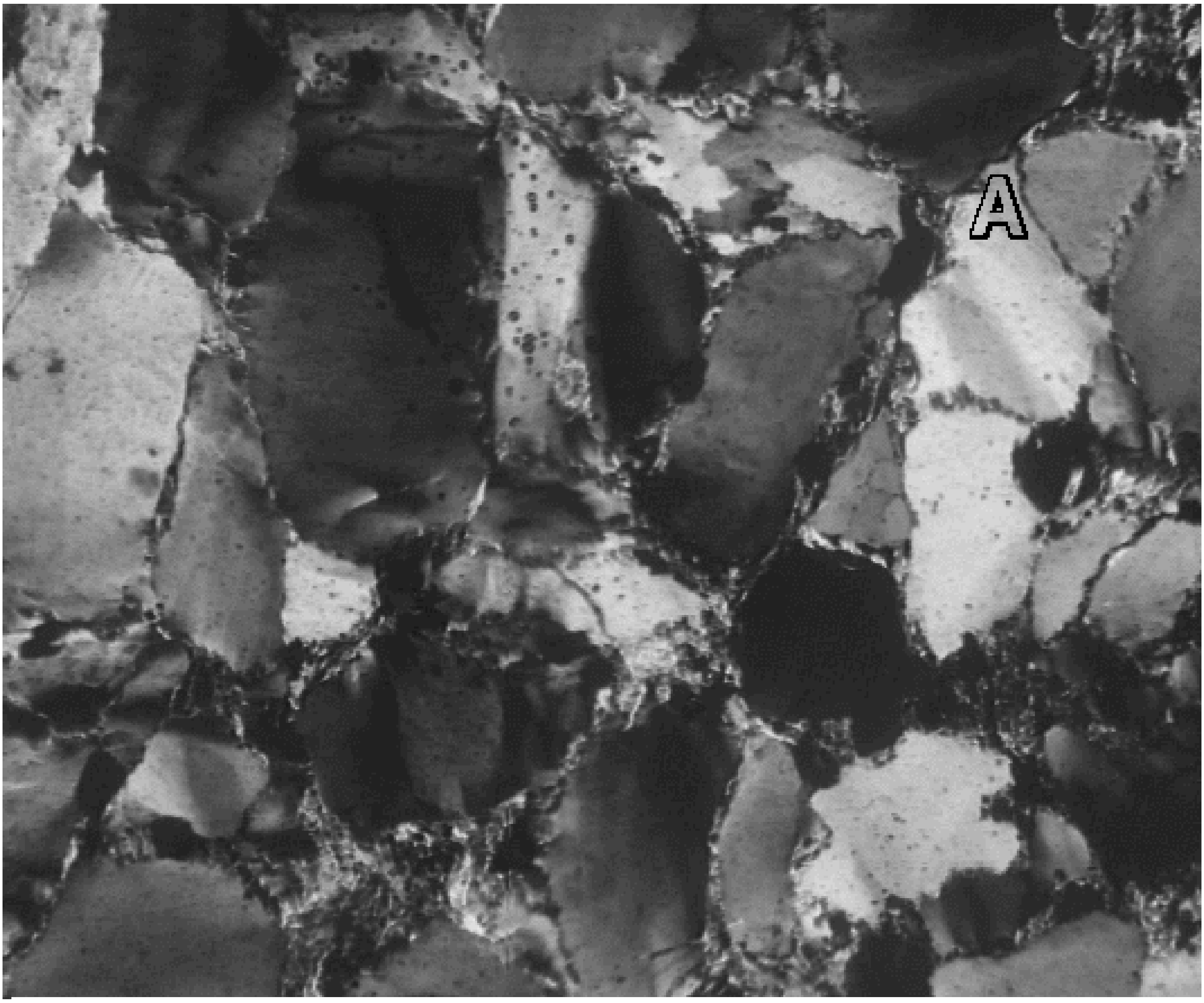
Lab 1c-Deformation Mechanisms

VIEPS/Mainz Microstructure Course

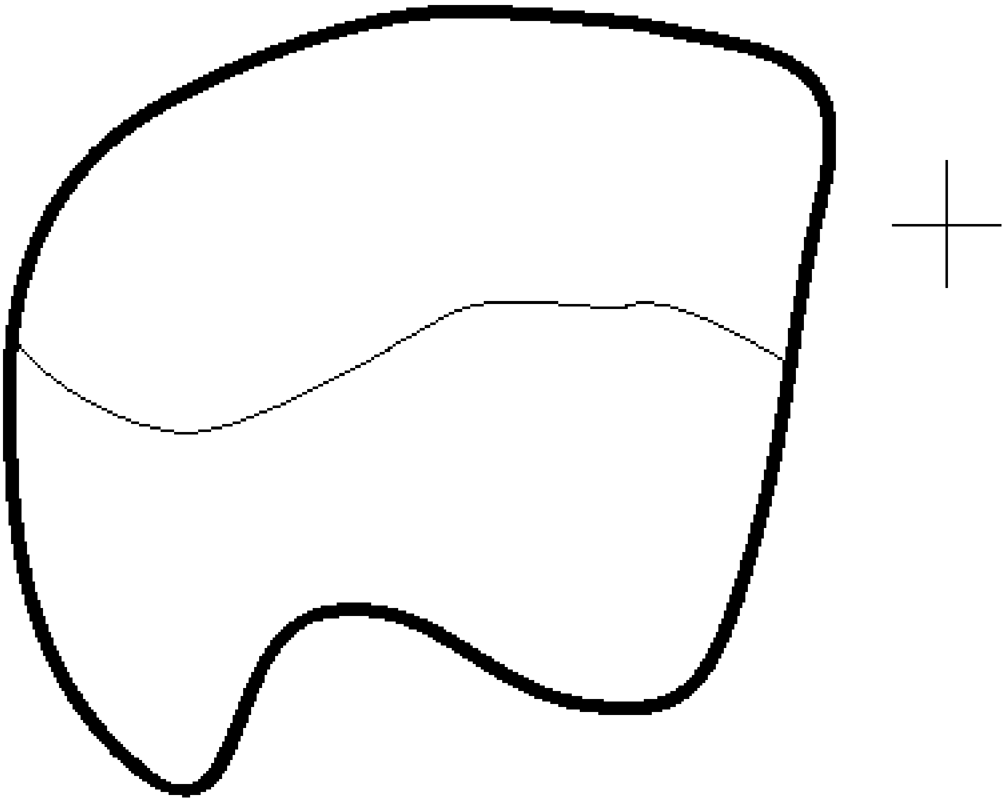
3) Evidence of crystalline plasticity in naturally deformed rocks.

These micrographs display a variety of deformation microstructures, for this practical only worry about those which reflect deformation by crystalline plasticity.

a) Quartzite Weak to moderate deformation of a quartzite with minor micas at low metamorphic grade. Original clastic quartz grains show numerous features of intra-crystalline plasticity, including deformation bands, and undulose extinction.



The figure below shows a quartz grain with the trace of the basal plane. Using a stippled pen, show what this grain would look like (ie its extinction characteristics) in crossed polarised light, assuming the polarisers are parallel to the cross.



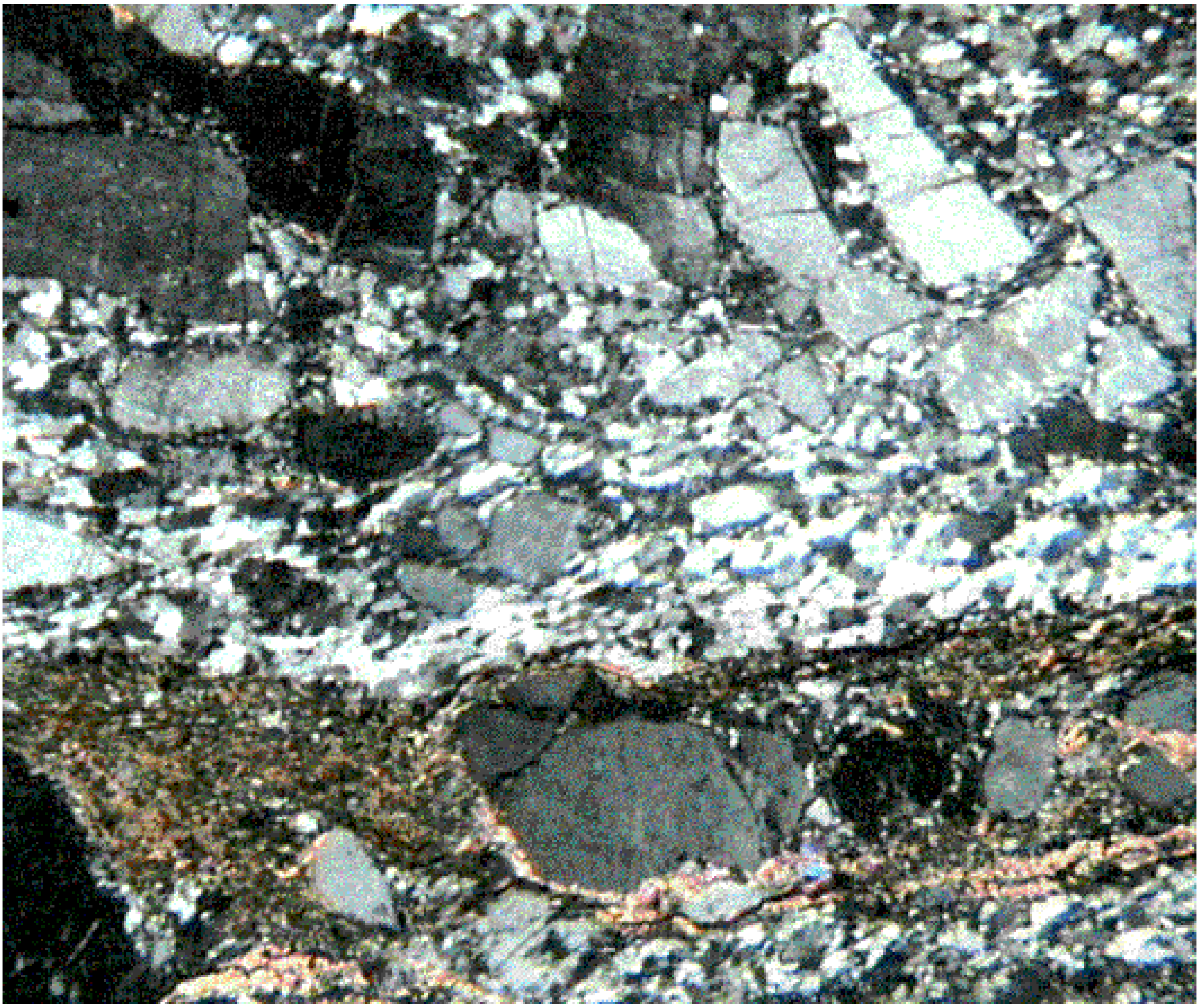
Now look at grain A in the top right hand corner, and make a sketch of its basal plane (assuming the dark bands are sub-perpendicular to the basal plane, as they usually are in low temperature deformed quartz).

b) Marble A typical low grade deformed marble, showing extensive twinning.

The quartz grains embedded in the middle of the calcite appear to be relatively undeformed, why?

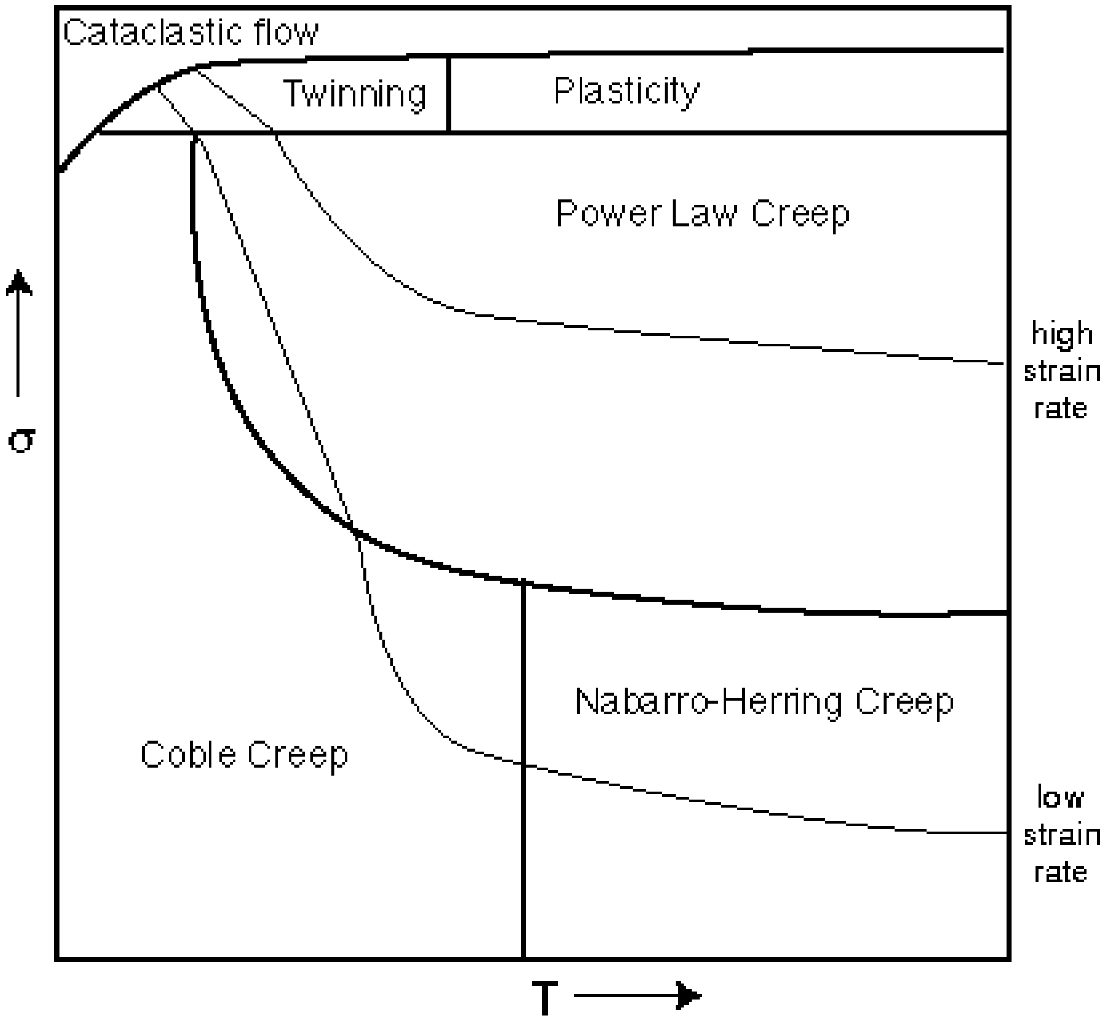
Why are the twin planes in the calcite curved?

c) Mt Kosciusko Granite



The quartz and feldspar in this granite appear to have deformed by quite distinct deformation mechanisms, why?

Place a cross on the generic deformation mechanism map below for both the quartz and the feldspar. On the same diagram show the calcite from the previous picture as an arrow showing its history.



The quartz grains have undergone at least a 10x reduction in grain size, how might this affect the mechanical response of the quartz?

Lab 2a-Recovery,Recrystallisation & Foliation Development

VIEPS/Mainz Microstructure Course

Further Reading:

An Outline of Structural Geology, 1976. Hobbs, Means & Williams p 73-104

Urai, Lister & Means 1986 Dynamic Recrystallisation of Minerals In : Mineral & Rock Deformation: Laboratory Studies Ed: Hobbs & Heard ,Geophysical Monograph 36.

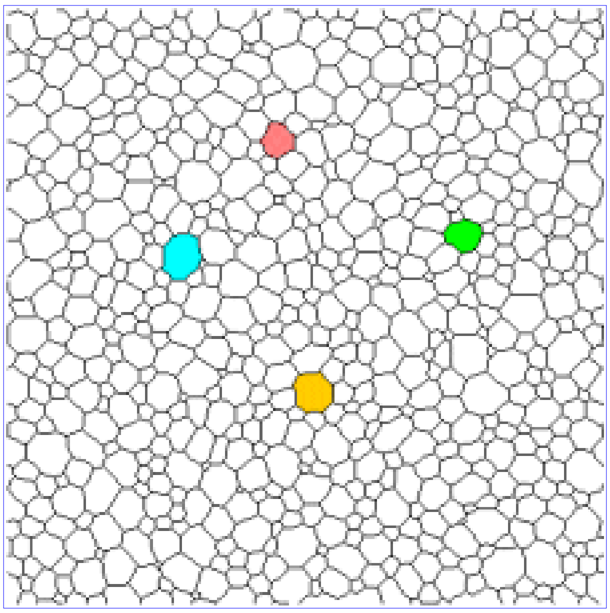
Jessell & Lister 1990. A simulation of the temperature dependence of quartz fabrics. In: Deformation rheology and tectonics. Ed: Knipe & Rutter, Geol. Soc. London Special Publication No 54. 1)

Computer simulations of deformation processes.

The first part of the lab consists of a series of computer simulations of various grain scale deformation mechanisms & processes.

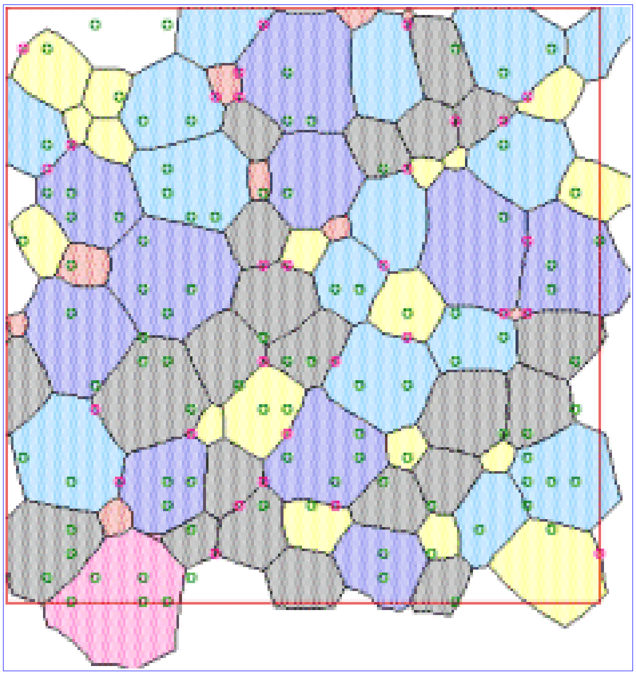
A) Static Grain Growth Simulation. This is a computer simulation of grain growth in a single phase rock, such as a quartzite or a marble, and was developed by Paul Bons. First of all go and have a look at the movie of grain growth, and then answer the question below. In this simulation the only driving force for grain boundary migration is the minimisation of surface energy via the minimisation of grain boundary curvature. The boundaries all migrate towards their centre of curvature. Static Grain Growth Movies: There are 2 movies called NORMAL GROWTH and PINNED GROWTH, and to run them double click on the icon and play with the slider control at the bottom of the window.

i) The NORMAL GROWTH movie shows the behaviour of a polycrystalline aggregate when left to its own devices, without deformation, at a high enough temperature that grain boundaries are mobile. As you can see the number of grains decreases, and hence the grain size goes up. Four grains have been coloured in so that you can follow them.



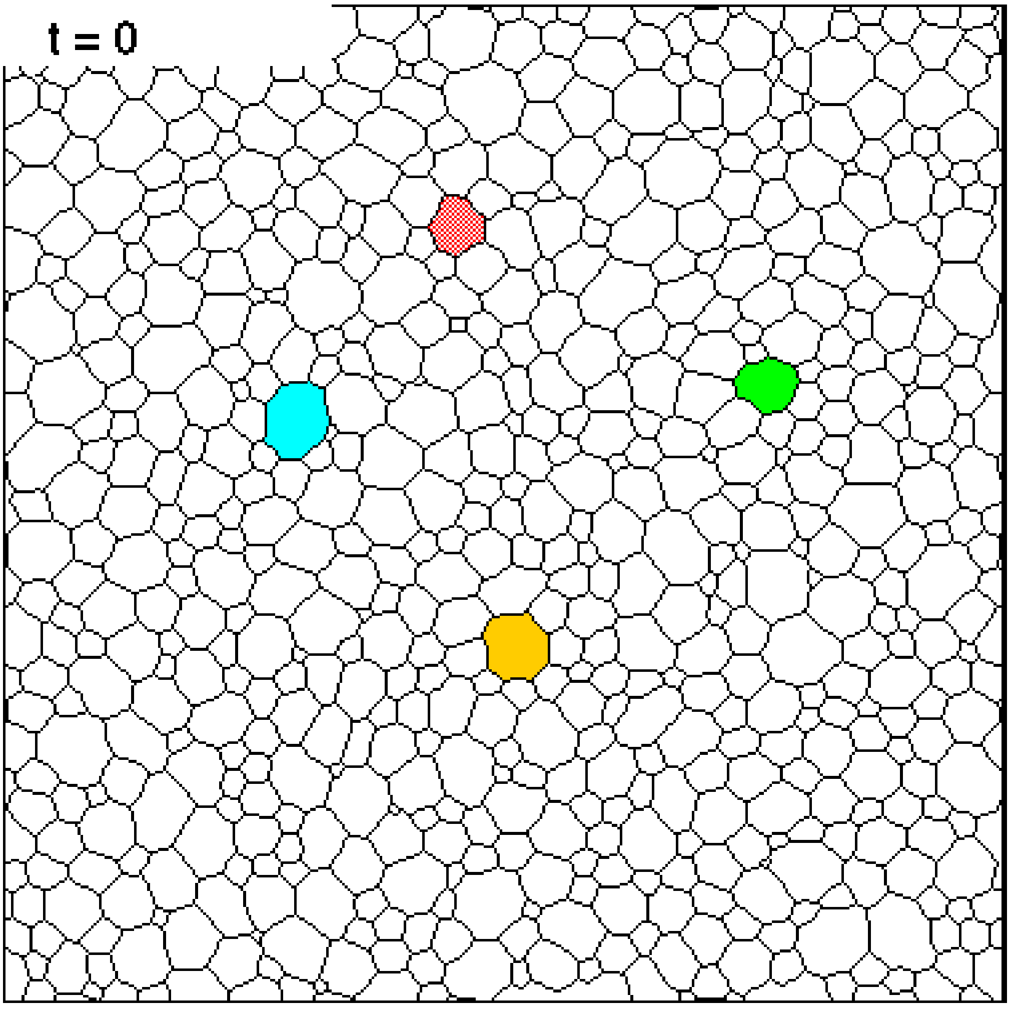
ii) The PINNED GROWTH takes over (at time =2000) from where the previous movie left off, except that a number of second phase particles have been added, and the grain boundaries find it hard to migrate through these particles. (These particles are green circles if they are found inside a grain, or red circles if they happen to be on a grain boundary). This is known as pinning and is very commonly observed in quartz-mica rocks, where the micas pin the grain boundaries. Notice how the grain growth virtually stops after a while. In this movie the colours of grain refer to the number of sides each grain posses (ie how many neighbours it has).

- Estimate what % of pinning particles are at grain boundaries at the start of the pinning sequence (t=2000) compared with at the end of it (t=12000).

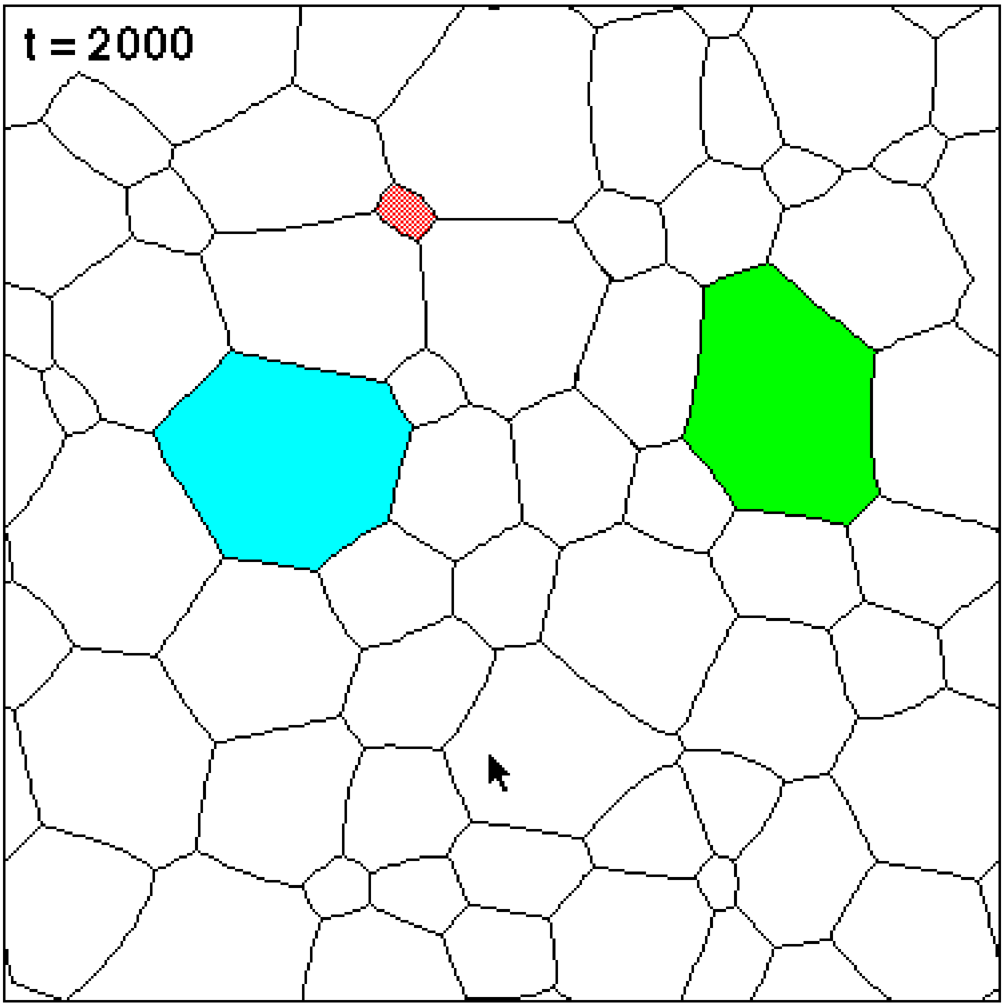


iii)

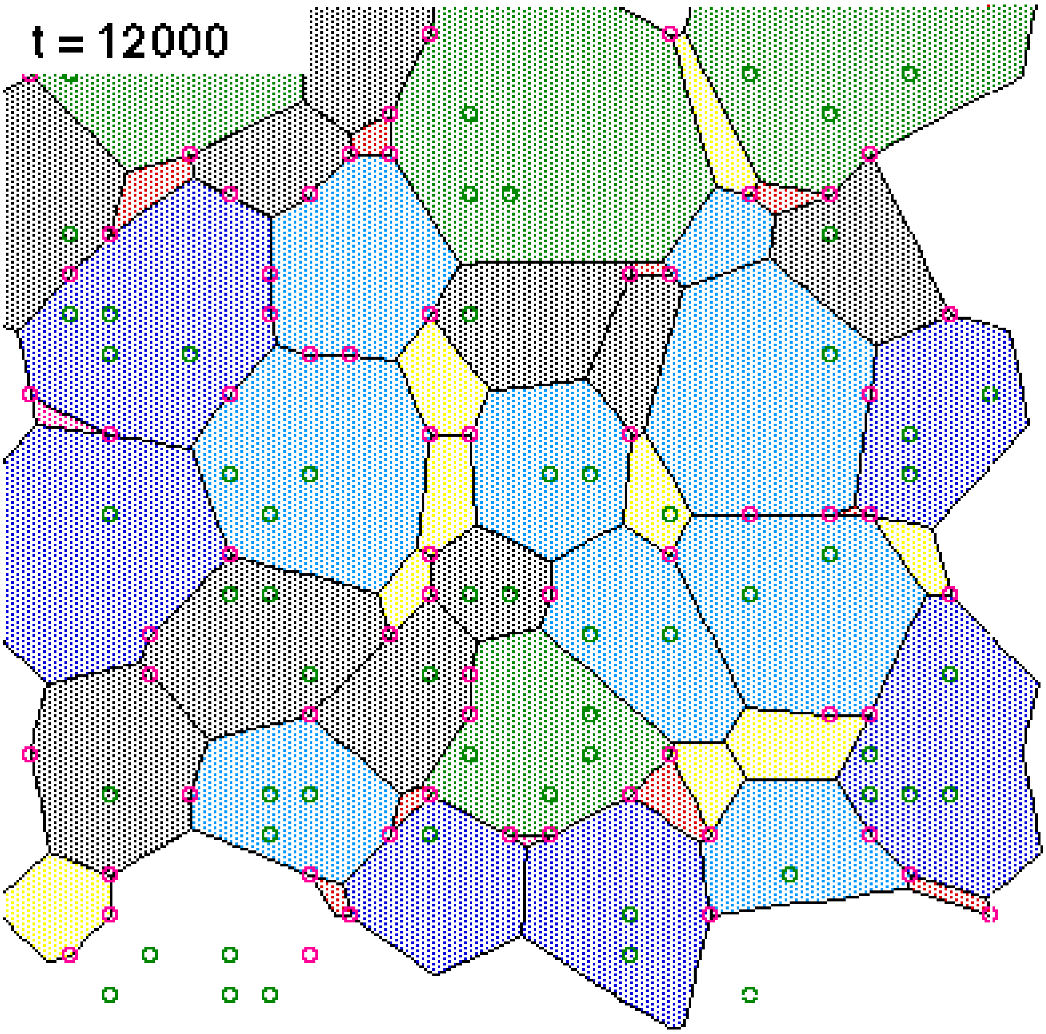
- For each of the three pictures below choose 20 neighbouring grains in the middle of the picture and count how many sides each grain has. (You will be provided with printouts of these pictures).



Start of simulation without pinning



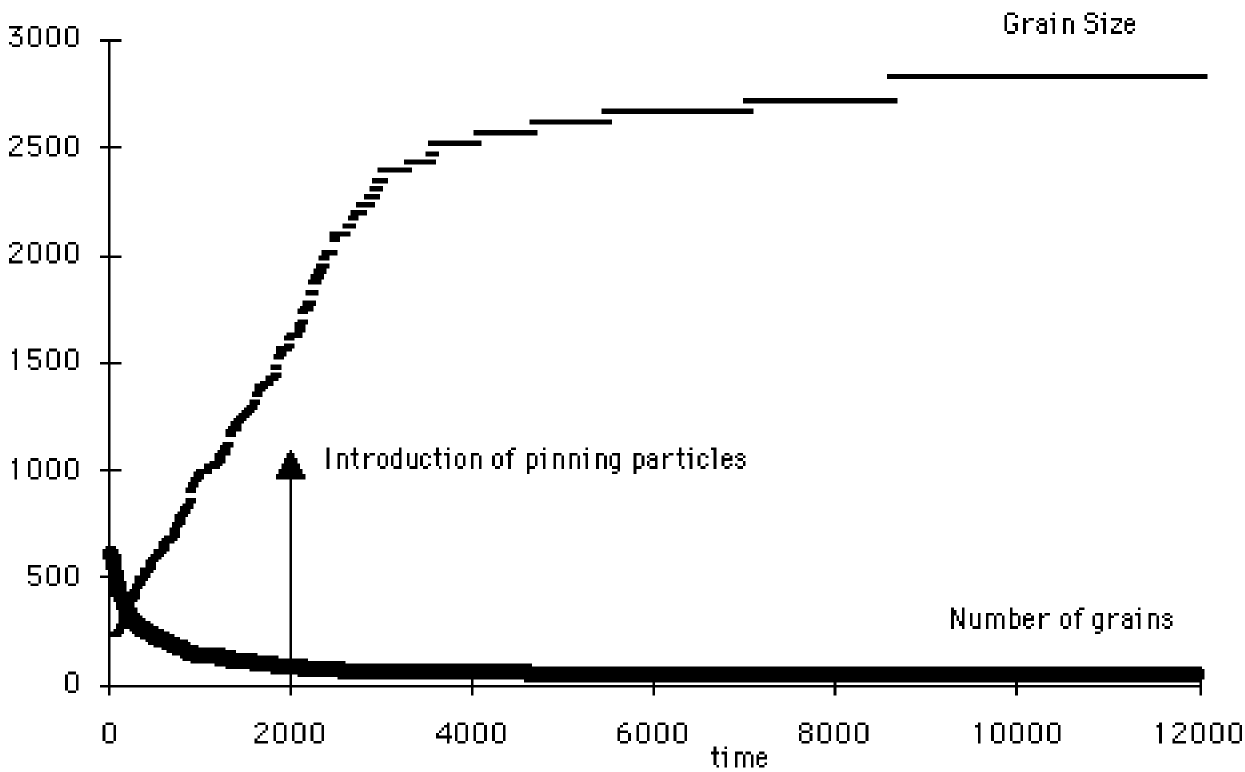
End of simulation without pinning



End of simulation with pinning

- What is the most common number of sides?
- Can you see any correlation between grain size and the number of sides a grain has?
- Can you see any correlation between the direction of curvature of grain boundaries and the number of sides a grain has?
- For each of your 20 grains guesstimate the narrowest angle between grain boundaries at a triple junction.
- What are the differences between the three stages for each of these observations?

iv) Now look at the graph of grain size versus time. The first portion of the grain size vs time graph is linear, but then it starts to roll over and become virtually flat.



- At what time does this change occur, and what is the cause of the change in behaviour and its timing?

Lab 2b- Recrystallisation in analogue materials.

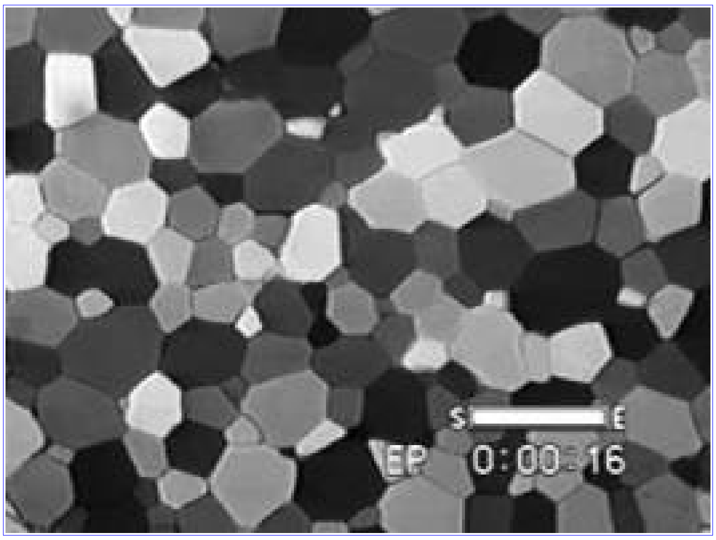
VIEPS/Mainz Microstructure Course

We have four movies of static, dynamic, and metadynamic recrystallisation in octachloropropane.

A) Grain Growth.

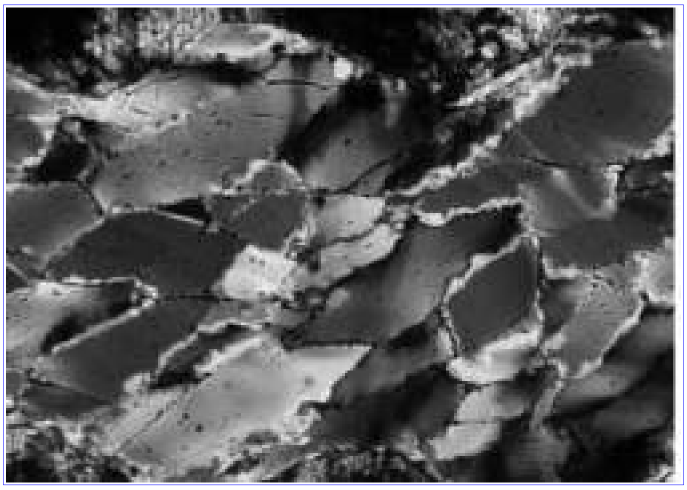
In this experiment, we start out with a nice foam texture, and end up with a nice foam texture, and inbetween we have a nice foam texture. This is characteristic of static grain growth.

- What are the characteristics of the grain boundary geometries seen in this experiment?
- Is there a relationship between the number of sides a grain has and the curvature of its boundaries?
- What is the driving force for grain boundary migration in this experiment?
- What is the relationship between grain size and whether a grain shrinks or grows?



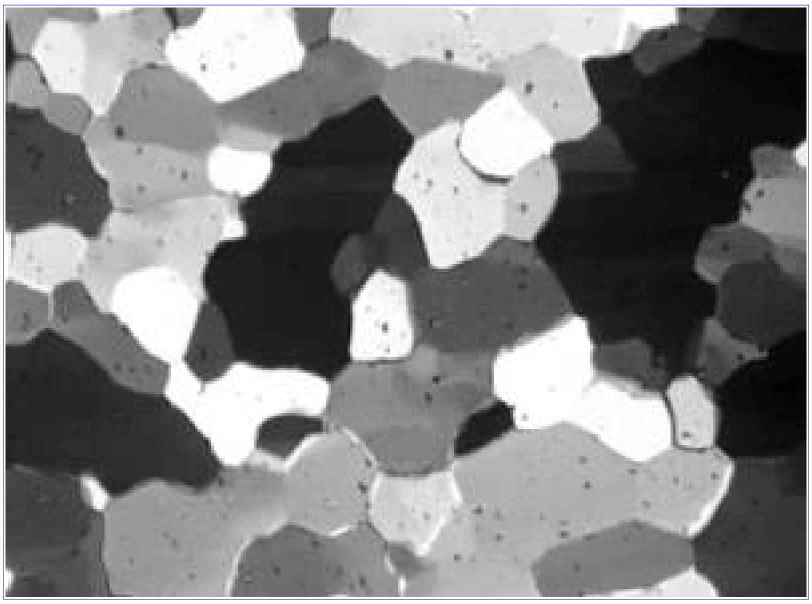
B) Dynamic recrystallisation. This movie is an extended version of one of the movies in the first lab. Now we can find out if your predictions for further microstructural development are true. The white areas that develop around grains show areas where the grain boundary is no longer perpendicular to the surface of the glass, so that you are looking through two grains separated by a grain boundary.

- Sketch the grains A & B at 4 stages of this experiment, and label the deformation processes involved in the evolution of grains A & B.
- Look at Grain C and its neighbours below it, how does the grain boundary change through the experiment, and why might this change occur?



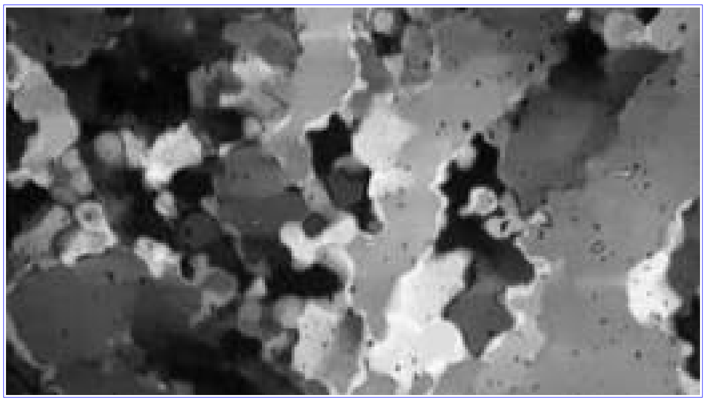
C) Dynamic and meta-dynamic recrystallisation. In this pair of movies we start off with a foam texture, deform it in pure shear, stop the deformation, and watch it return to a foam texture. At the end of this first movie the motor was stopped and the further evolution of the microstructure is controlled by its internal state at that time.

- Using the dust particles as markers of material points, how much shortening has the sample undergone by the end of the first movie?
- What is the direction of maximum flattening, and is this parallel to the grain shape foliation orientation?



Pure shear deformation of OCP

- In the second movie (below) the behaviour of the aggregate is very different in the first half of the movie than in the second half, how and why does the behaviour change (eg why might the driving forces evolve even though the motor has been turned off) ?



Post deformation behaviour of OCP following pure shear as seen above

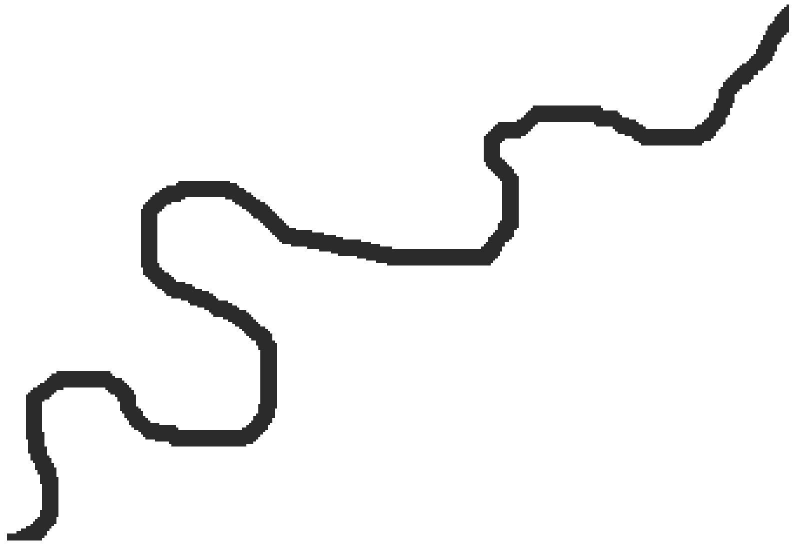
Lab 2c- Evidence of recrystallisation in naturally deformed rocks.

VIEPS/Mainz Microstructure Course

Serrated Grain Boundary Formation.

Pictured below is a natural example of a serrated quartz grain boundary. Serrated grain boundaries can form by the local migration of the boundary in opposite directions. The same microstructure could also form by the migration of the boundary in one direction only, but at different velocities.

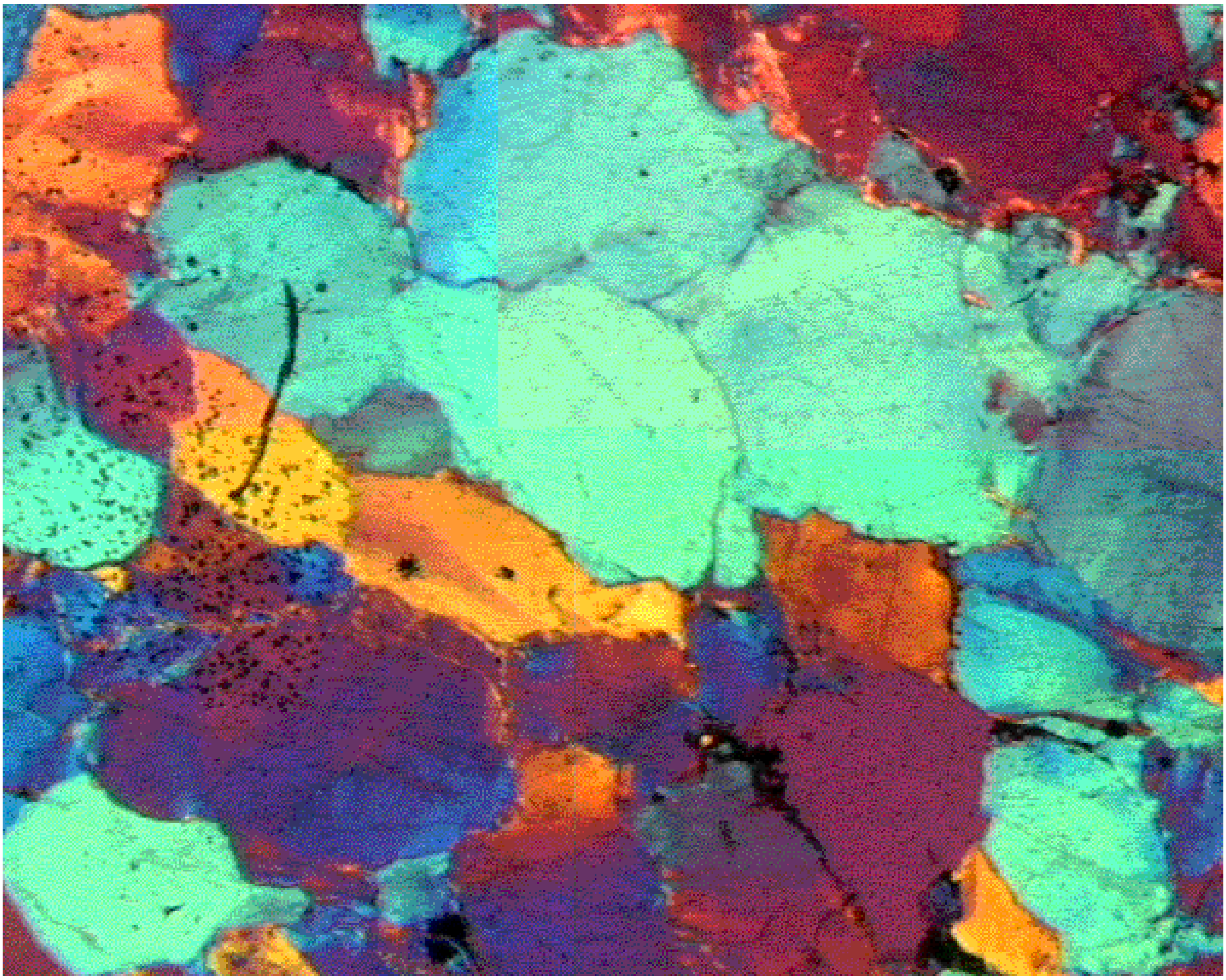
- What reasons can you think of as to why the grain boundary might migrate at different speeds or directions along its length?



In this lab we shall re-examine the quartzite from the first lab in terms of its place in a sequence of progressive deformation. ie the deformation geometry and metamorphic conditions are stable, but the microstructure evolves as different processes dominate.

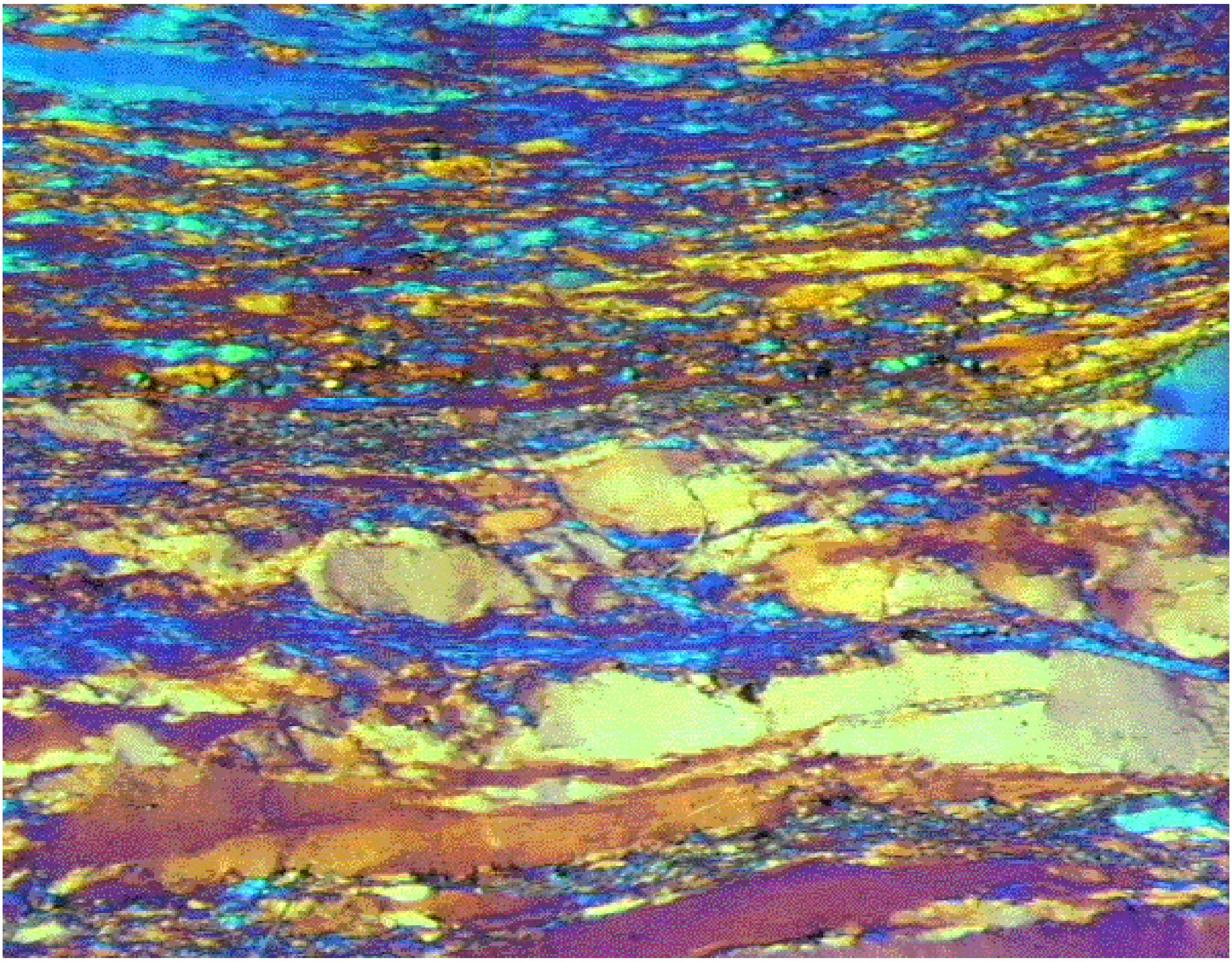
7/1A or M1 [5 or 3] This is the same sample we saw in the first lab. This time look at it in terms of the sequence that follows.

- What happens to the Grain Shape Foliation (GSF) & Crystallographic Preferred Orientation (CPO) as we progress through this sequence?



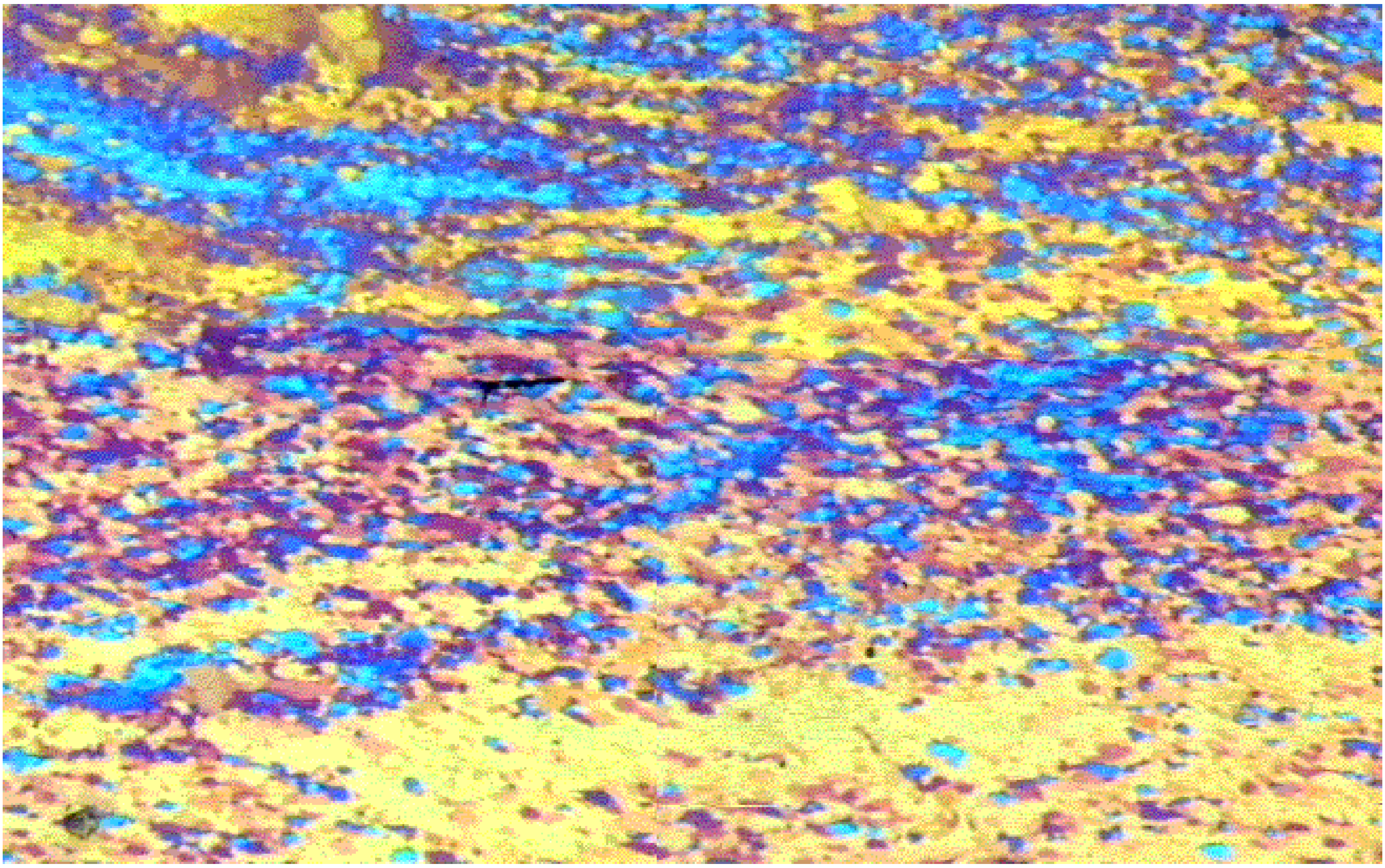
7/1B or M2 [5 or 6] Same rock, more strain. The ratio of new recrystallised (small) grains to old grains has changed, and many large grains are no longer in contact with each other, at least in 2D.

- What reasons might there be for more strain to be accommodated by the small newly recrystallised grains than the big old grains?
- What do these small grains do to your estimates of strain? What are the average aspect ratios of the small grains versus the large ones?



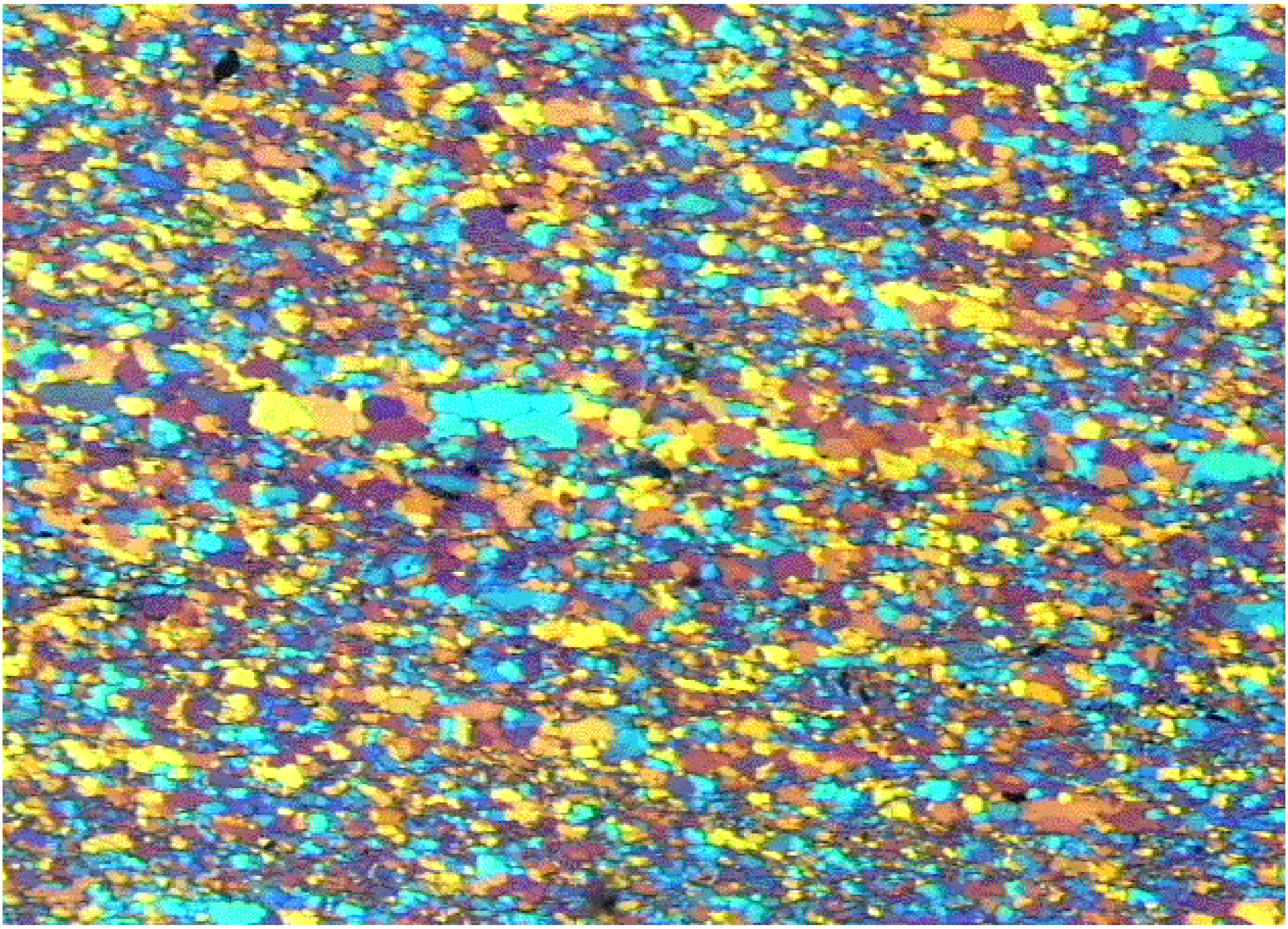
7/1C or M3 [3 or 4] Same rock, even more strain. The average grain size in this sample is now much smaller than M1 or M2. .

- Notice that the specimen shows clusters of grains with similar orientations, how might this domainal fabric develop?



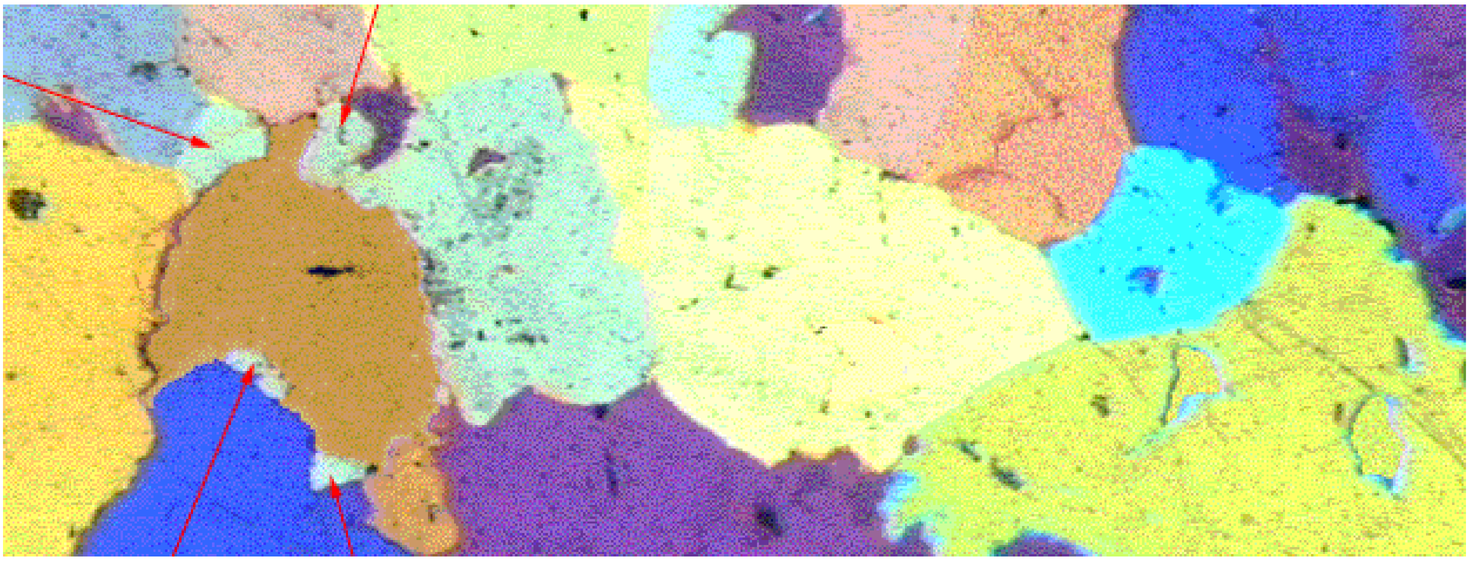
7/1D or M4 [5 or 9] Same rock, more strain than a grain can stand. Is the grain size now uniform in this rock, if not why might it not be.

- Are we still seeing the intra-crystalline microstructures we saw at lower strains? What deformation mechanisms might have been active in this rock?



73-1307 Cooma Quartzite [9] In this quartzite the microstructure is markedly different from the previous suite of rocks, and this is in part due to the higher temperature during deformation.

- Document the differences between this specimen and the previous ones, and explain the likely causes for the deformation microstructures in this rock.
- Notice the orientation family highlighted by the 4 red arrows, how did this microstructure form?



Lab 3a-Foliations and CPOs

Further Reading:

An Outline of Structural Geology, 1976. Hobbs, Means & Williams p 73-104

Urai, Lister & Means 1986 Dynamic Recrystallisation of Minerals In : Mineral & Rock Deformation: Laboratory Studies Ed: Hobbs & Heard ,Geophysical Monograph 36.

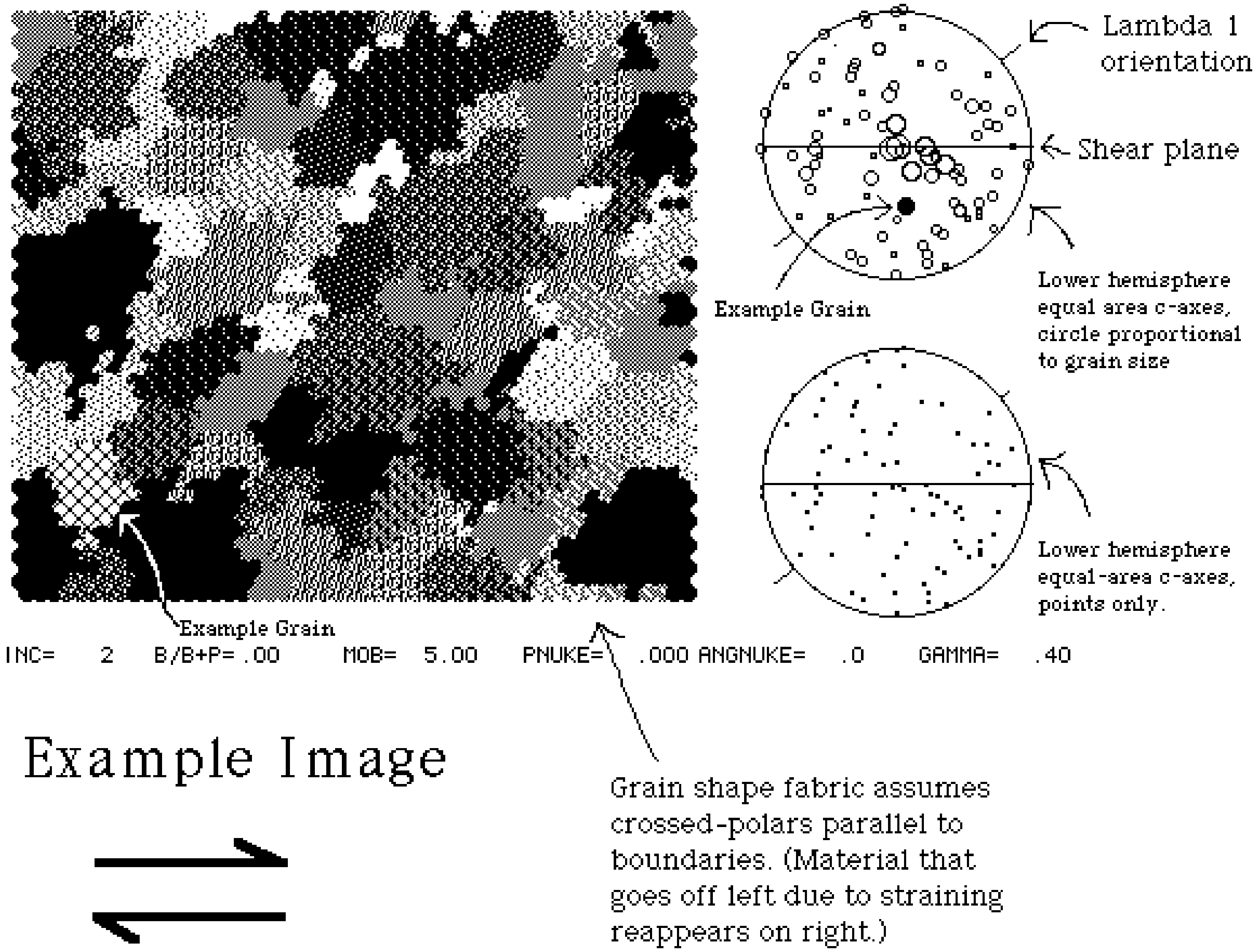
Jessell & Lister 1990. A simulation of the temperature dependence of quartz fabrics. In: Deformation rheology and tectonics. Ed: Knipe & Rutter, Geol. Soc. London Special Publication No 54.

1) Computer simulations of crystallographic preferred orientation development.

The first part of the lab consists of a computer simulations of crystallographic preferred orientation and grain shape foliation development in quartzites.

- **Crystallographic Preferred Orientation=CPO**
- **Grain Shape Foliation=GSF.**
- **Lambda 1 is the orientation of maximum finite elongation.**

Example Image The following image shows an example of what you should expect to see for each increment of deformation, and explains all the various features.



These simulations are calculated assuming that four deformation processes are involved, homogeneous simple shear, lattice rotations according to the Taylor-Bishop-Hill model, (which calculates the lattice rotations for a crystal based on its orientation, the applied deformation, and how easy it is for each slip system to be activated) grain boundary migration driven by dislocation density contrasts, and rotation recrystallisation at or near grain boundaries. The hidden assumptions are that the dislocation density in each grain is a function of how easily it deforms which is in turn a function of its orientation. Grains which require less stress to make them yield will have lower dislocation densities and will thus preferentially consume other grains, and will also more slowly develop subgrains by rotation recrystallisation.

The 3 simulations are set up to reflect increasing temperature, which will affect:

i) the Critical Resolved Shear Stress (CRSS) for different slip systems (ie how much stress resolved into a slip plane in the slip direction is needed to induce dislocation glide).

ii) the mobility of grain boundaries

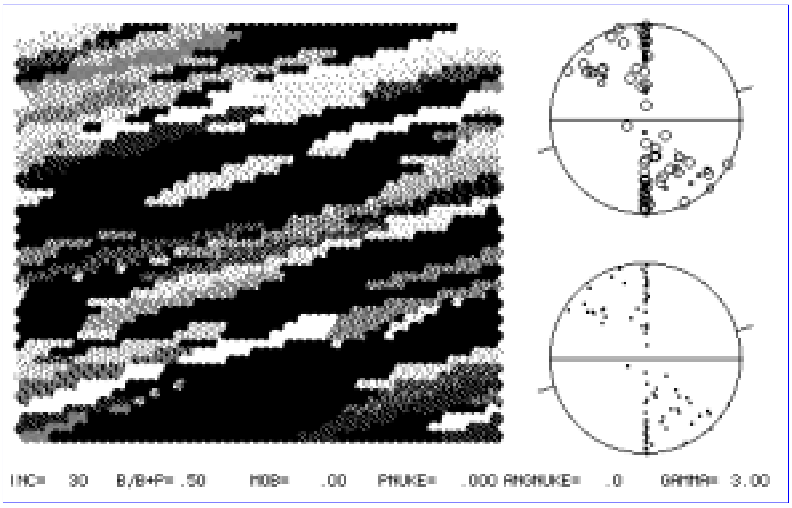
iii) the rate of recovery

iv) the rate of rotation recrystallisation.

In order to simplify things we have assumed that the two dominant slip systems in quartz are basal and prism , although in fact other slip systems would probably operate as well. At low T (eg Greenschist facies deformation) basal slip is believed to have a lower CRSS than prism , whereas at higher T (eg granulite facies deformation) the situation is reversed. As a result two things happen: the patterns of lattice rotations vary (although not by all that much) and the grain orientations which have lowest dislocation densities will change. For the each simulations follow the grain size and c-axis orientation history of 4 grains from different parts of the stereographic projections (the same 4 grains each time) and contrast their relative fates.

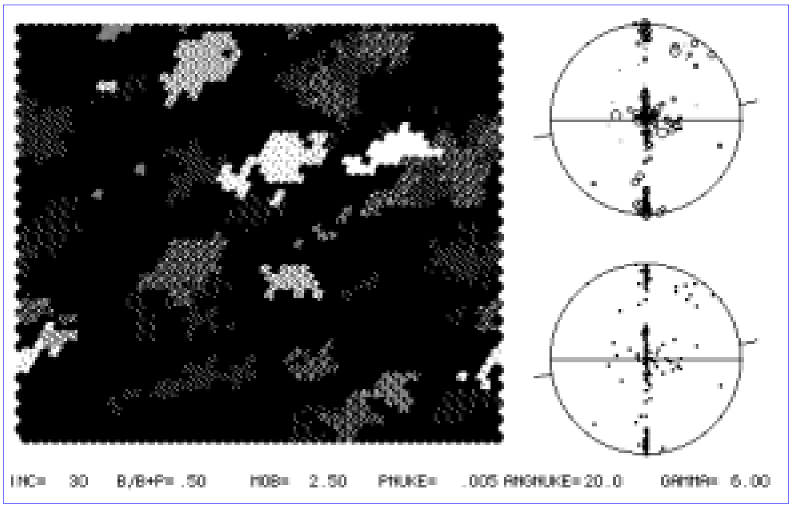
A) Low temperature. At very low temperatures the mobility of grain boundaries is so low that grain boundary migration is effectively suppressed. In this extreme example there is no recrystallisation at all, either GBM or RR. This is not very plausible, but it gives you a good control on the effects of lattice rotations on their own.

- What is the relationship between initial and final grain sizes, and the orientation of the final GSF and Lambda 1 (principal finite extension direction)?

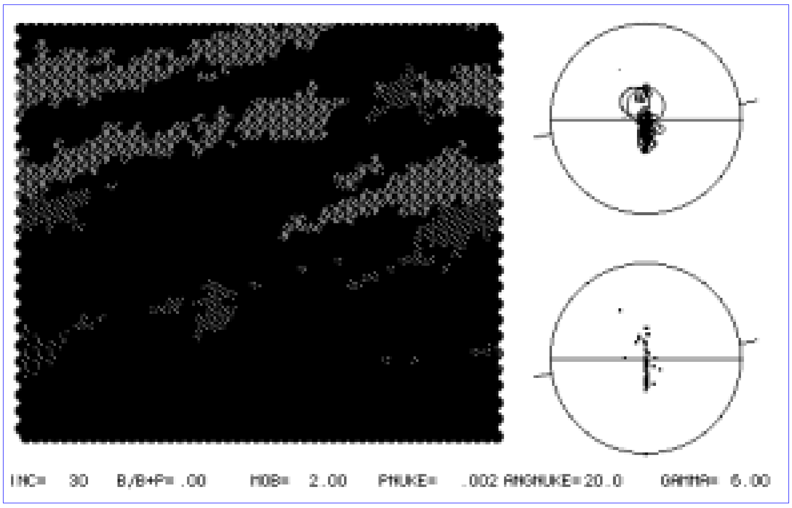


B) Medium temperature. (cf Fig B & D below) At higher temperatures the mobility of grain boundaries is higher so that grain boundary migration velocities increase and but we also get significant rotation recrystallisation occurring.

- What is the relationship between initial and final grain sizes, and the orientation of the final GSF and Lambda 1? What is the relationship between c-axis orientations and grain size by the end of the simulation.



C) High temperature. (cf Fig A & C below) At even higher temperatures the mobility of grain boundaries is higher again, although the overall velocity of grain boundaries will be moderated because the driving force is lowered as rate of internal recovery will also be higher. Rotation recrystallisation is lessened, because more slip systems are available, and the strain contrasts between grains is thus reduced.



- What is the relationship between initial and final grain sizes, and the orientation of the final GSF and Lambda 1?
- What is the relationship between c-axis orientations and grain size by the end of the simulation?

2) Natural CPOs in quartz

The following c-axis fabrics were all measured from regions thought to have deformed predominantly in simple shear. These fabrics were pulled from the literature by me, (based on my wish to find natural analogues for the model results) so don't blame the authors for these comparisons, and don't take them too seriously. Further details of these fabrics, and the original reproductions of them, can be found in the references given. Unfortunately they are plotted in two different orientations with respect to the shear plane, so be careful. (S=foliation, L=lineation).

Which of the simulations above correlate with which natural patterns below?

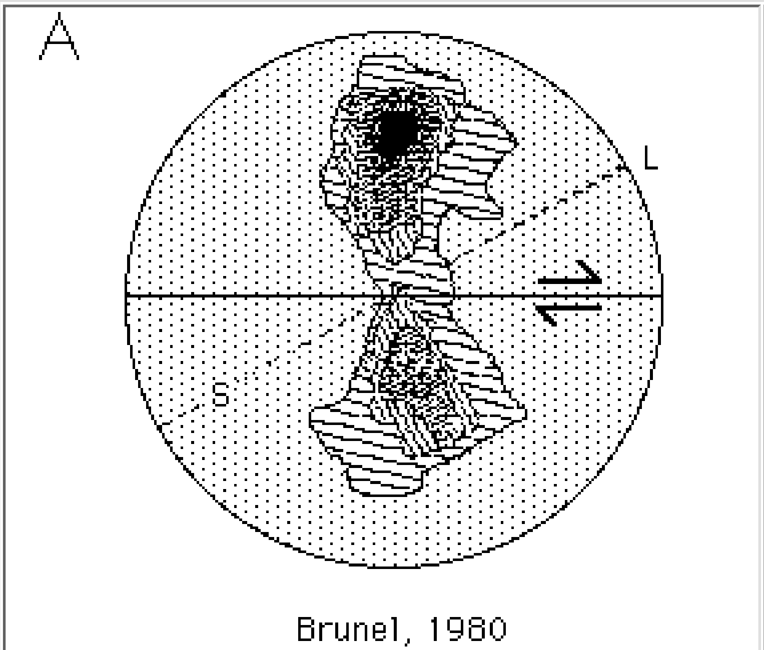


Fig A Brunel, M. 1986. Tectonics 5, 247-267.

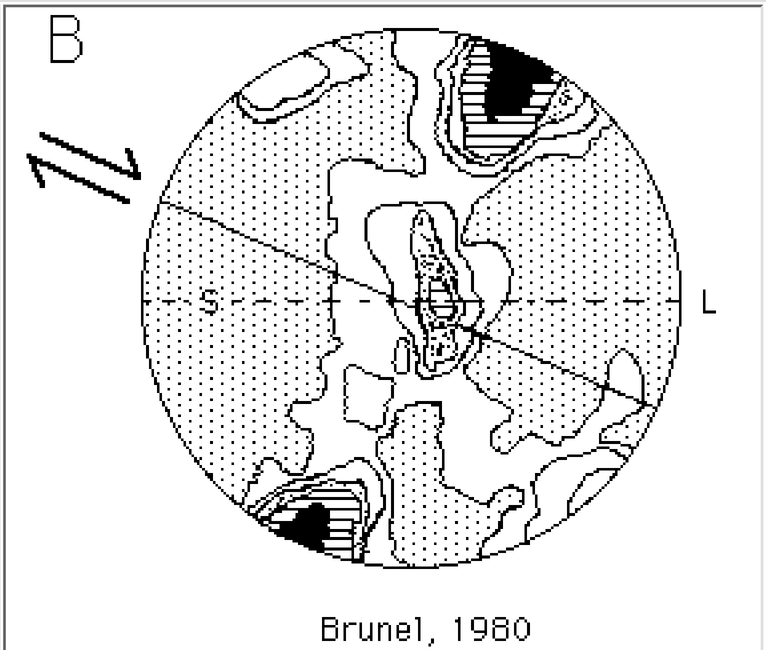


Fig B Brunel, M. 1986. Tectonics 5, 247-267.

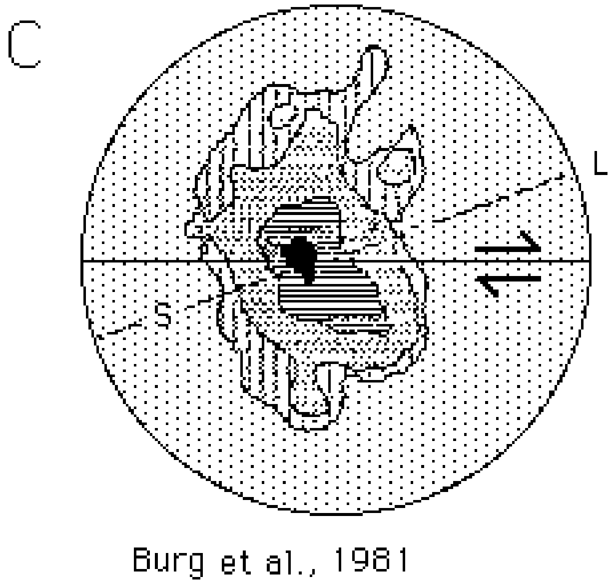


Fig C Burg, J.P. et al., 1981. Tectonophysics, 78, 161-177.

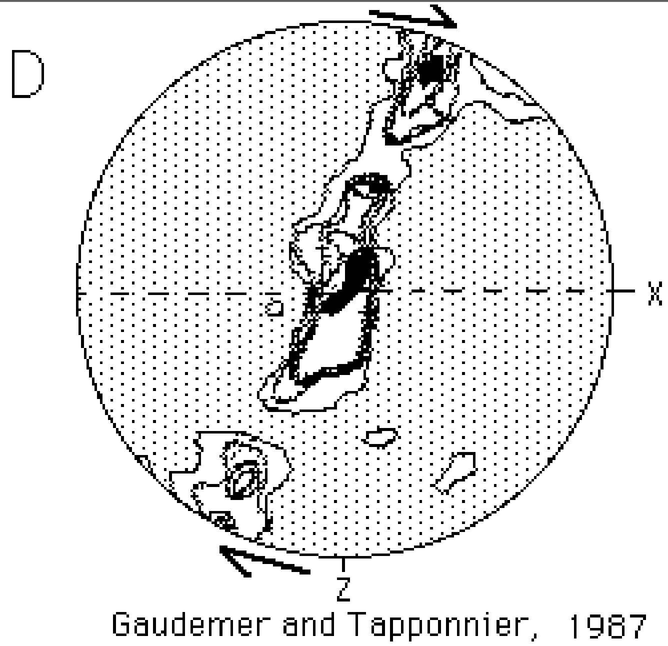


Fig D Gaudemer, Y and Tapponnier, P. J. Struct. Geol. 9, 159-180, 1987.

Lab 3b- Quantative image processing of microstructures.

VIEPS/Mainz Microstructure Course

So far we have taken a fairly qualitative approach to measuring microstructures, however if you actually want to compare microstructures from different areas it is much better to have an accurate measure of, for example grain size distribution or modal analysis. The main problem with this is that it is really boring to do. In this exercise we will divide the class up into 4 groups and each group will measure the grain size distribution, grain shape foliation orientation and aspect ratio of one of the four quartzites you looked at in the last lab.

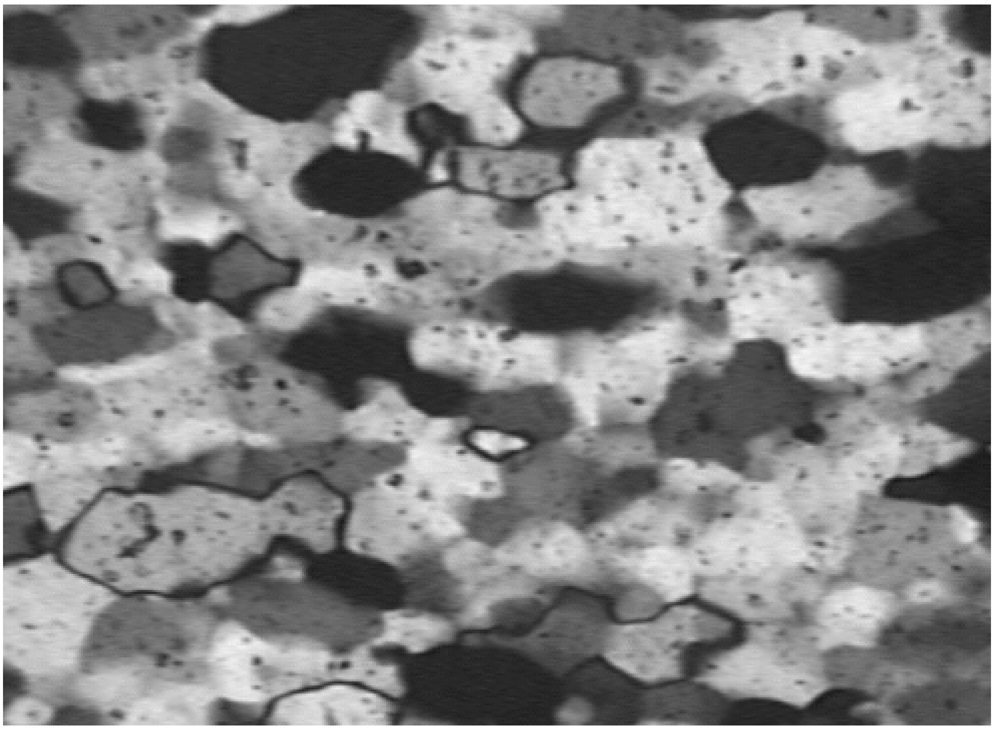
In order to do this we have used the video microscope to capture "grey scale" images of the thin sections, and you will use the image analysis package called "**NIH-Image**" to perform this analysis.

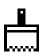
Grain Size, Grain Shape, Grain Shape Foliation

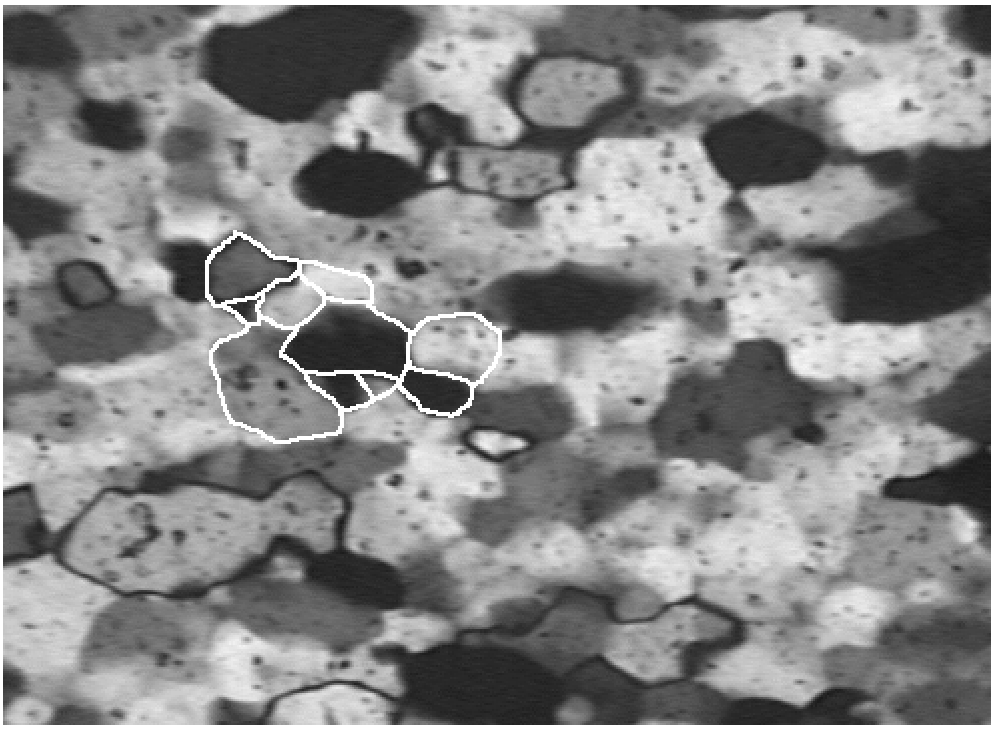
These parameters are often measured through pretty laborious manual techniques, and assuming that you are interested in the analysis of differences in values, then the following technique is not too time consuming...

The basic steps of the analysis are:

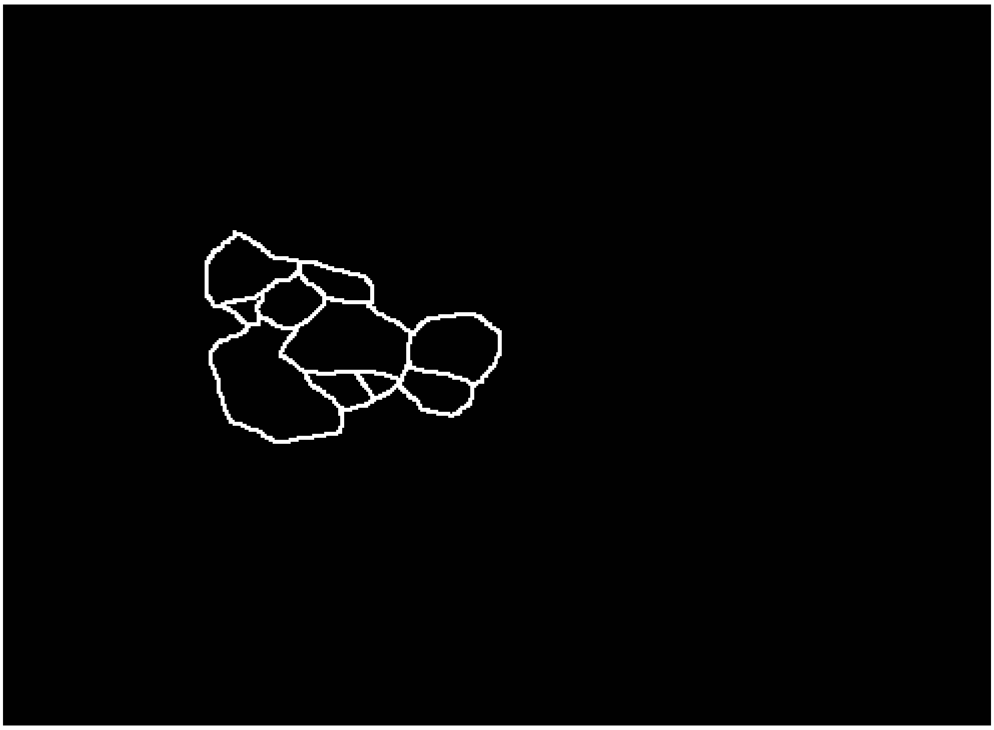
0) Open up the file **16xqtz.pict** using the **Open** option from the **File** menu, this is a photo-micrograph of a deformed quartzite.



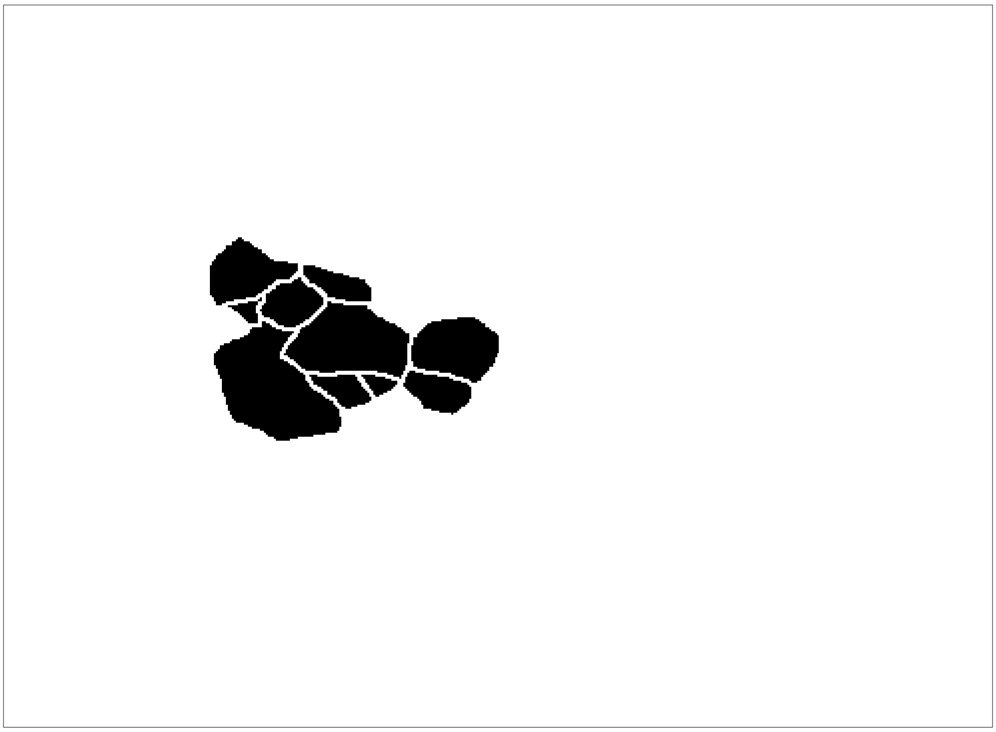
1) Trace boundaries of all the grains using the  tool, making all the boundaries white.



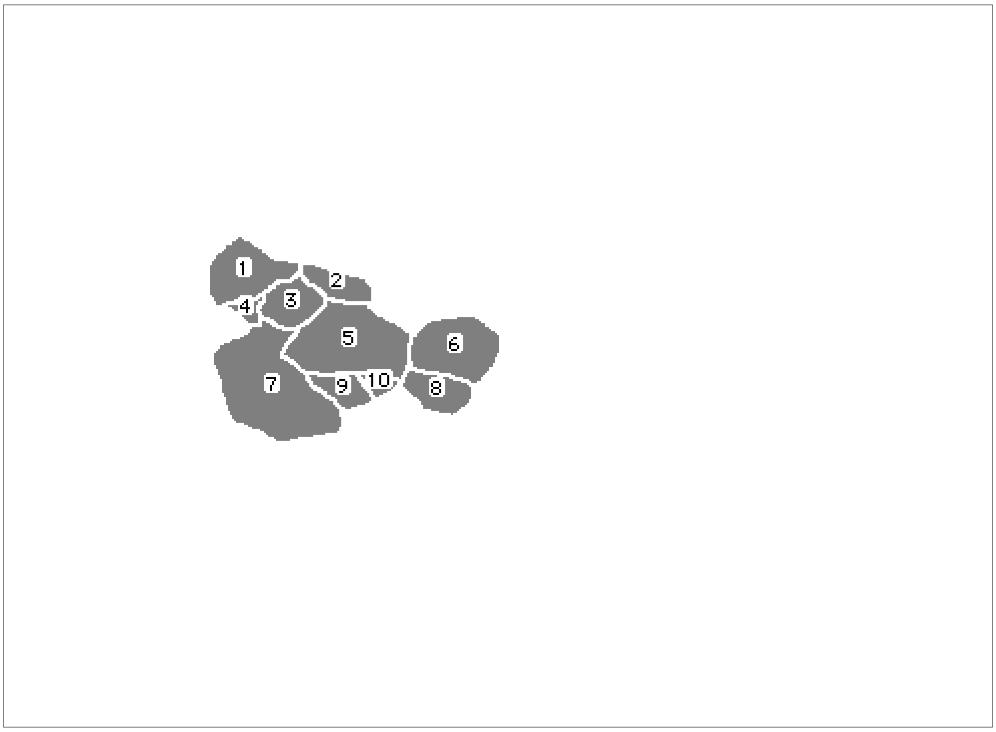
2) Turn the image into a thresholded image: select **Threshold** from the **Special** menu. This will duplicate the image and convert it to black and white.



3) Using the bucket tool, fill the outside areas with white.



4) Analyse the grains outlined in the new image: select **Analyse** from the **Special** menu. This will also open up a new window with all the grain size information for each grain.



5) Save this text information out to file by using the Save option from the **File** menu.

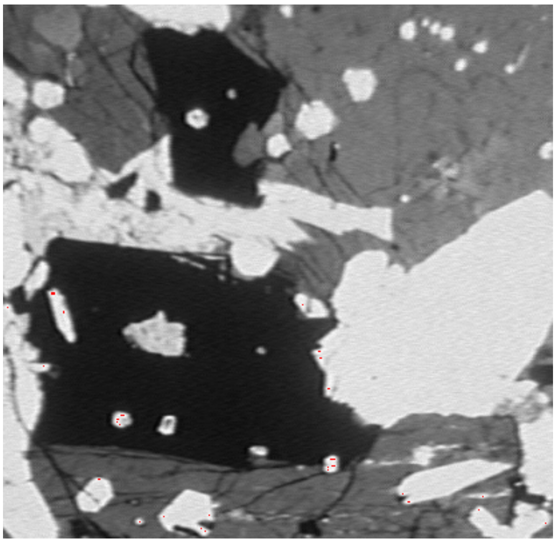
	Area	X	Y	Length	Majc
1.	867.00000000	120.06228638	227.90310669	126.71067	
2.	365.00000000	167.21369934	221.83013916	88.769554	
3.	510.00000000	143.59803772	212.30979919	88.225395	
4.	99.00000000	121.41413879	208.66667175	50.8700561	
5.	1637.00000000	173.05680847	192.70310974	171.4385	
6.	1079.00000000	226.07598877	189.96662903	128.2254	
7.	2242.00000000	133.52453613	169.77565002	214.5513	
8.	483.00000000	217.06211853	167.85920715	91.497474	
9.	305.00000000	169.70492554	169.06230164	79.254837	
10.	111.00000000	187.55856323	171.73873901	46.284271	

6) Read in this new text file from **Cricket Graph**, and make frequency plots (I'll tell you how in the class).

Modal Analysis

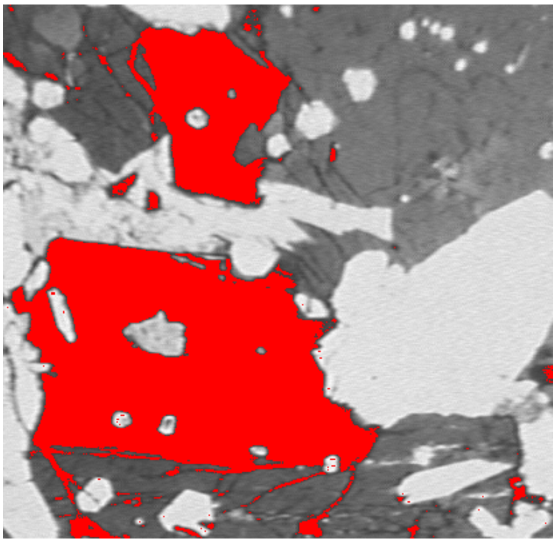
For certain rock types, such as this gabbro, it is possible to do a semi-automated modal analysis instead of point counting, and these techniques work even better if you have colour images.

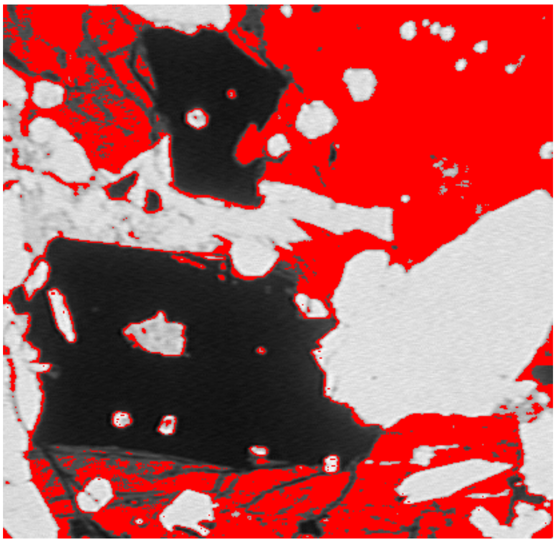
1) Load in **gabbro.pict** file. In this image the dark grains are magnetite, the greay grains are amphiboles, and the light grains are feldspars.

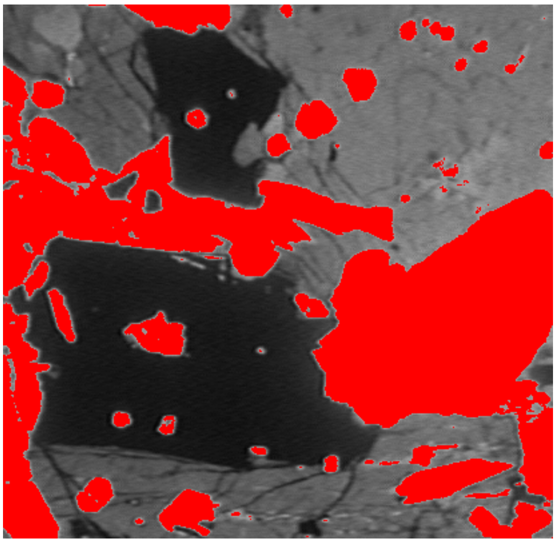


2) Threshold the image to individually highlight the magnetite, amphibole & feldspar domains.

For each thresholded image create a histogram, which will show the number of pixels of black and white, and hence the proportion of that mineral which is present in the image. Notice the problems that arise with respect to alteration along cracks.





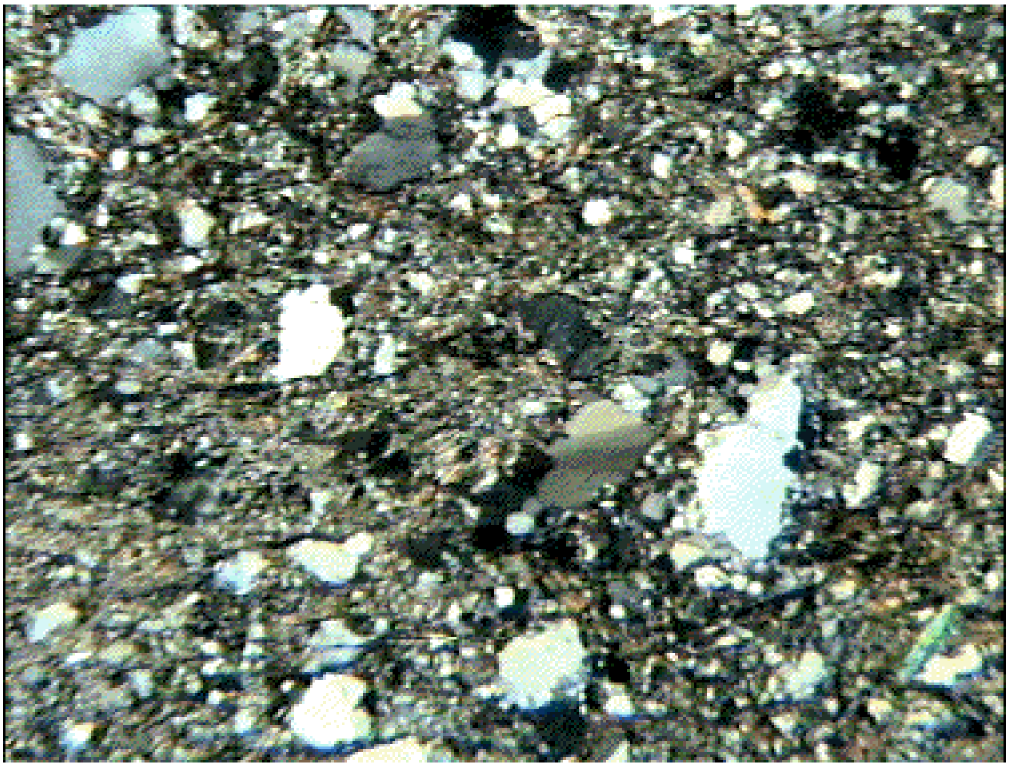


magnetite amphibole feldspar

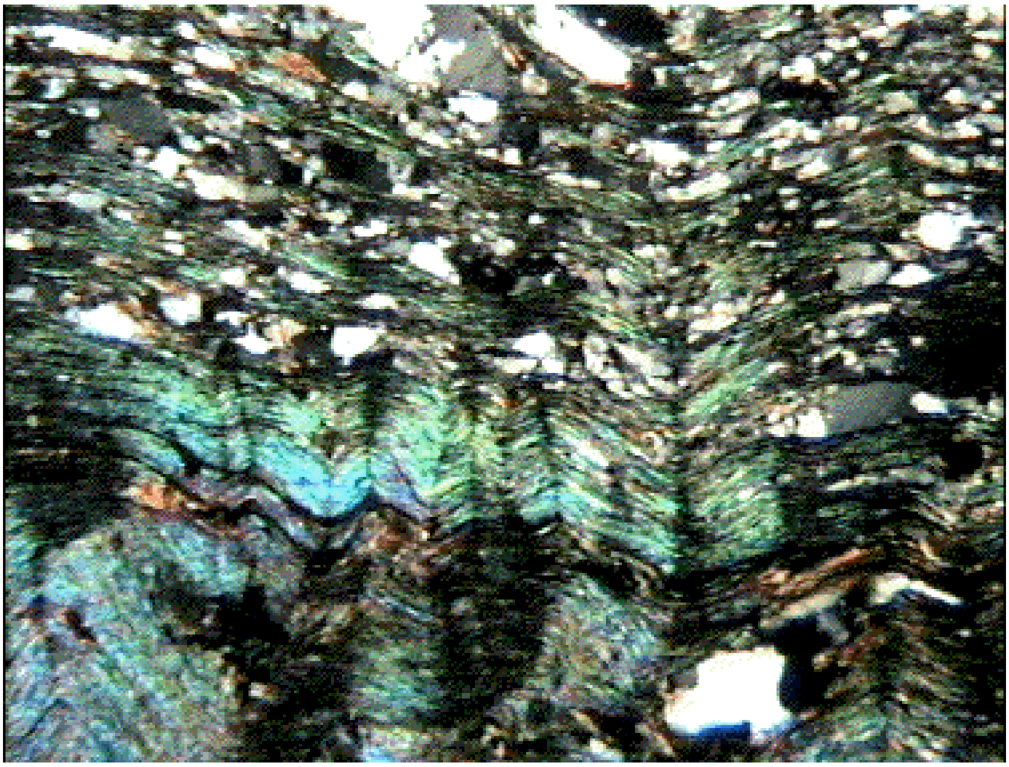
Lab 3c- Foliation development in naturally deformed rocks

73-0711 Foliated Greywacke This thin section demonstrates a common problem in low grade metamorphic terrains: how to distinguish sedimentary foliations from metamorphic/structural foliations.

- Make a sketch of any features which can be used to show whether this rock has undergone any deformation at all.

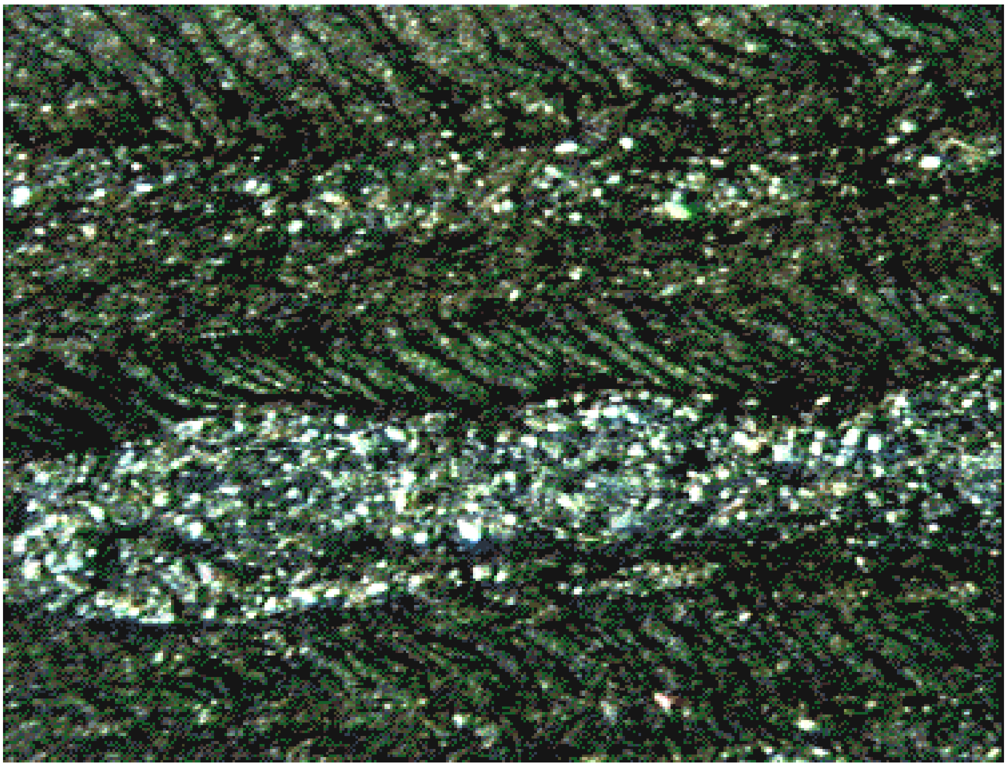


● **73-0716 Chlorite-Biotite-Muscovite Phyllite** This thin section shows the strong development of an initial foliation which has been overprinted by a strong set of intersecting and coalescing kink bands. Notice how the foliation is being transposed by the kinks into a new orientation, and how the angular nature of the kinks turns to more rounded shapes in the quartz rich zones.



Lake Glenmaggie slide This thin section also shows at least two strong overprinting relationships. Sketch the relationship of the foliations present in this rock, and describe the processes which appear to have been involved in the formation of each foliation. Notice the strong lithological control on foliation development.

Make a composite sketch showing the relationships between each foliation, and show the trace of the earlier foliations as they get reoriented by later events.



Lab 4A-Porphyroblasts & Shear Zones

VIEPS/Mainz Microstructure Course

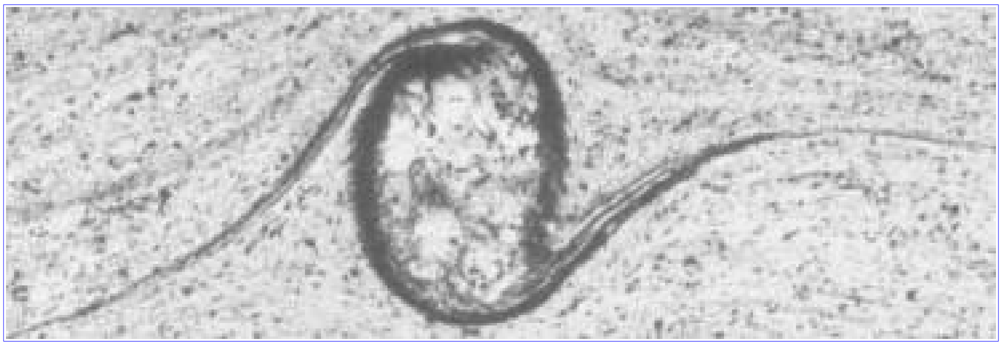
Further Reading:

An introduction to Metamorphic Petrology, 1989. Yardley Chapter 5 170-177

Shear-sense indicators: a review, 1991 Hanmer & Passchier Geol survey of Canada Paper 90-17

1) Experimental deformation of rock analogues

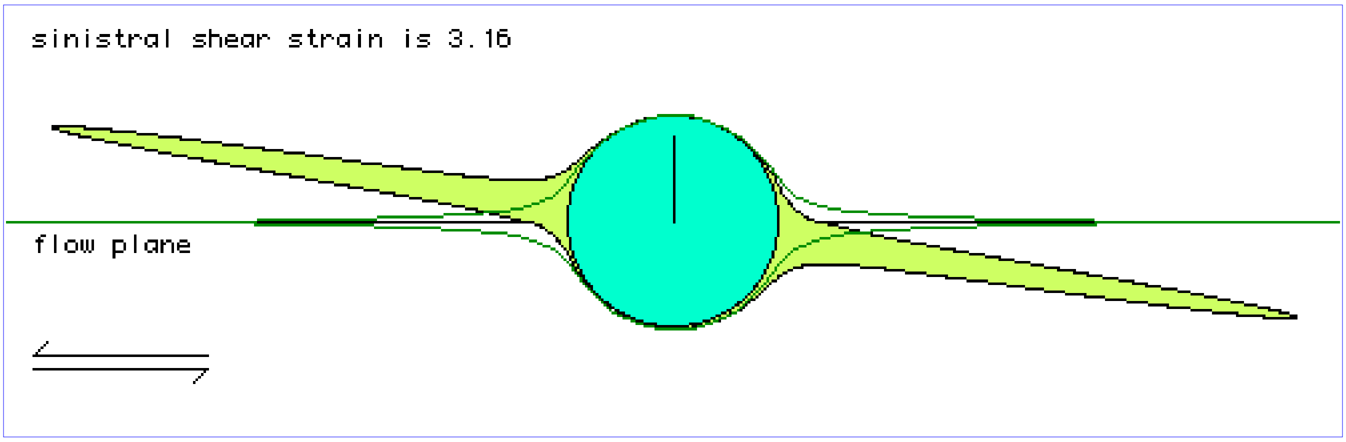
This movie shows the progressive simple shear deformation of a camphor clast in a matrix of OCP grains. This work was carried out by Coen ten Brink at the University of Utrecht. The rig is torsional, so that the shear zone boundaries are curved.

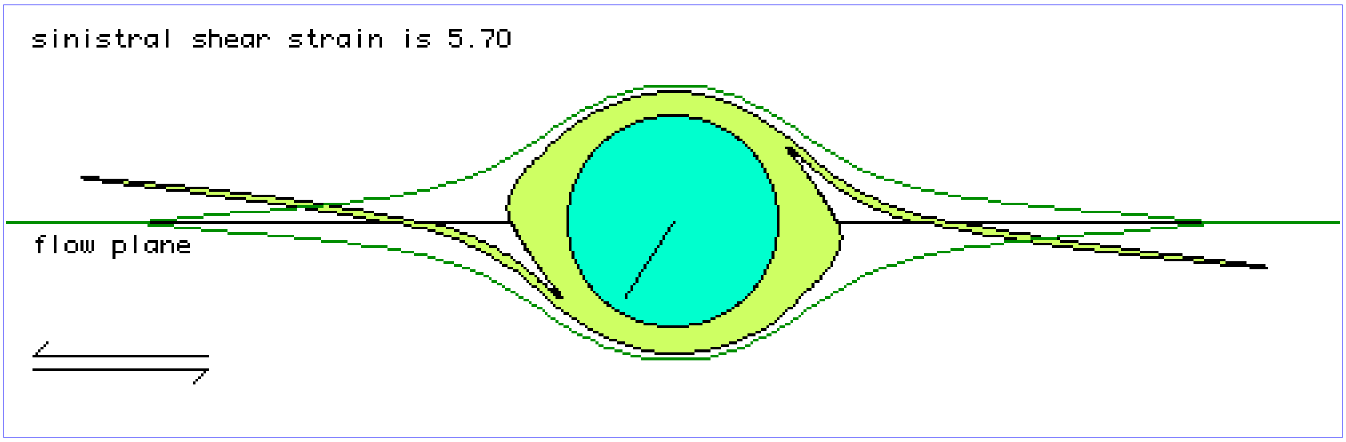


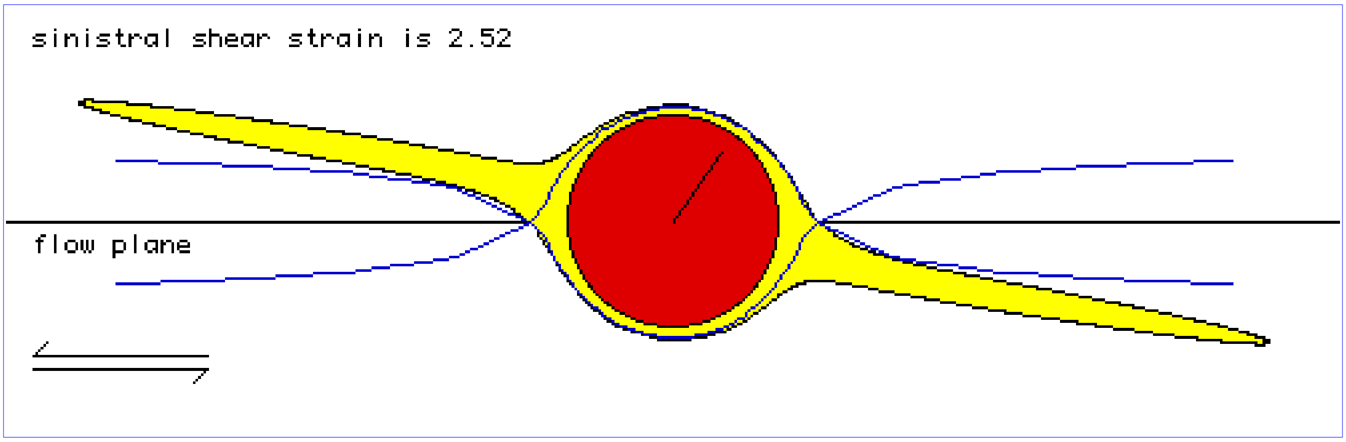
2) Movies of mantled porphyroclasts

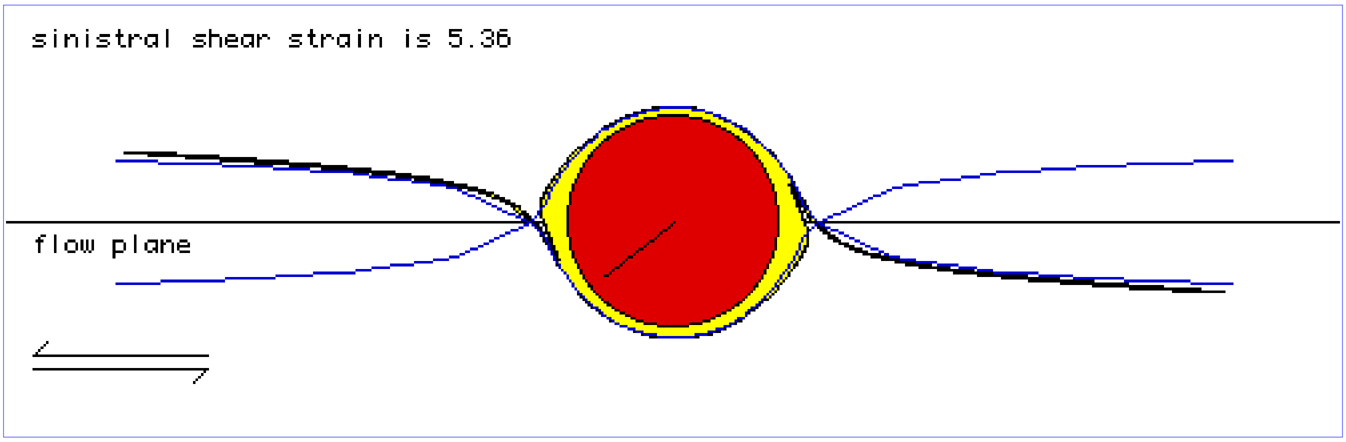
The following four movies show computer simulations of the development of mantled porphyroclasts in simple shear, for 2 different flow patterns and for 2 different initial widths of the passive mantle.

Watch the movies and answer the questions below.









For each movie, describe (sketch) and name the wing geometries that develop. If there are transitions of wing geometries with progressive shear strain, describe them. It is best to do this in the form of a table:

shear strain: 0......................1......................2......................3......................4......................5

movie #5: ....<------- theta ----------> <-----stair-stepping delta--------->

For each of the movies, explain the development in wing geometry in terms of flow pattern, initial mantle radius and amount of strain.

For each of the movies and the developing wing geometries, can you use them as sense of shear indicators if (a) you know the orientation of the flow plane and (b) if you **don't know** the orientation of the flow plane?

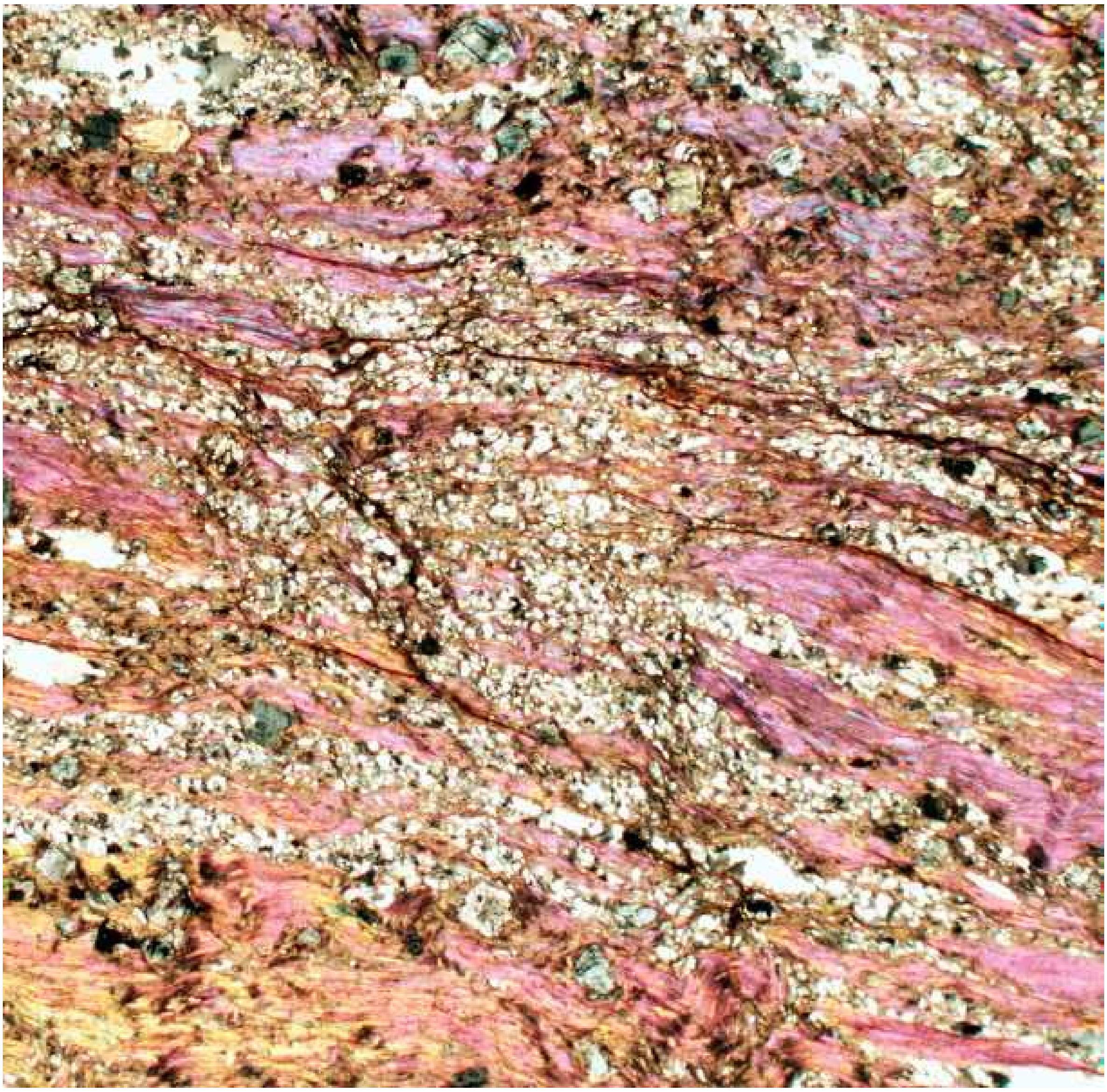
Continue with lab 4.B

Lab 4B-Porphyroblasts & Shear Zones

3) Complex porphyroblast/matrix relationships

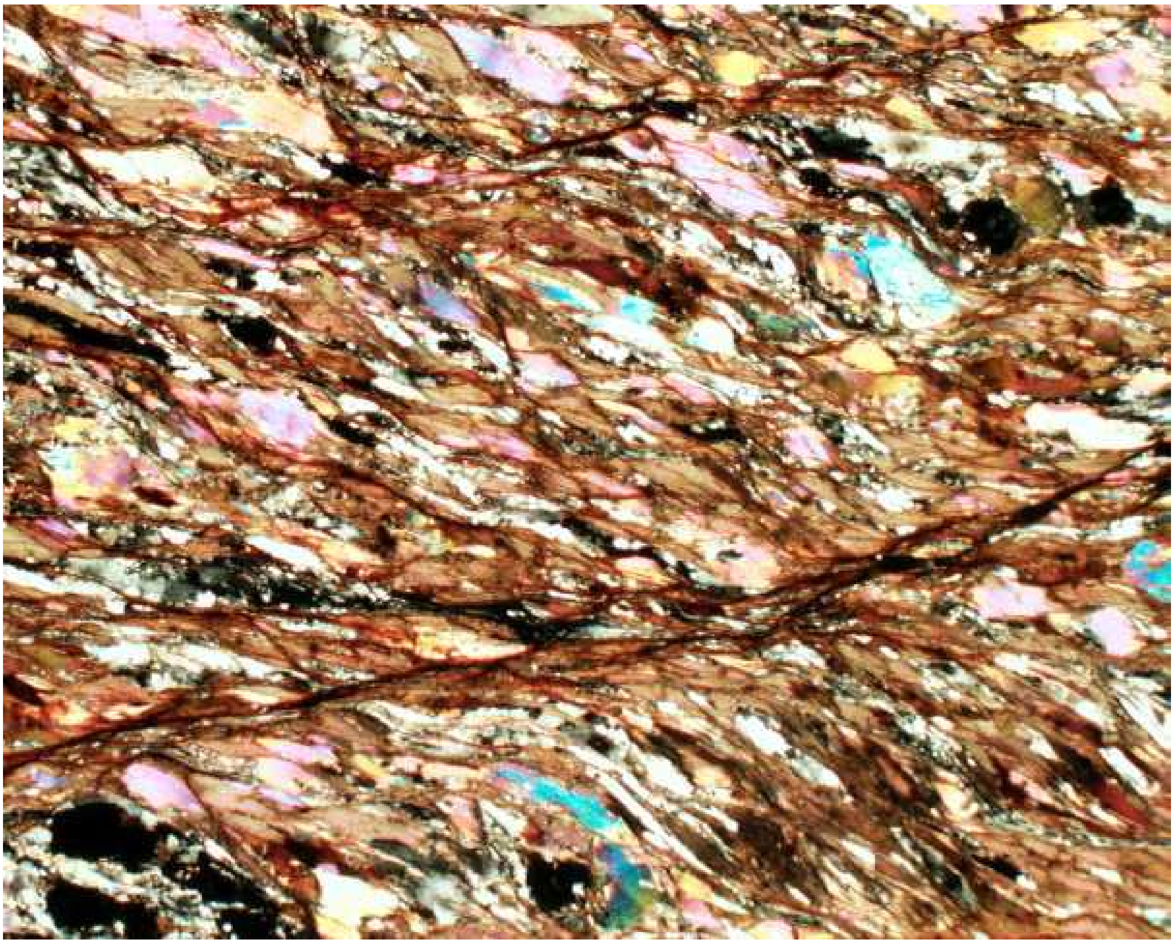
- For each rock draw a diagram concentrating on porphyroblast/matrix relationships. Label/identify and sketch at an appropriate magnification the internal inclusion trails in the porphyroblasts, with respect to the external fabrics. Determine what the timing of porphyroblast growth is with respect to the deformation.

RJ90410, from near Kiewa, eastern Victoria. Quartz-muscovite-biotite schist, with andalusite porphyroblasts containing abundant graphite-rich inclusion trails: hunt around for the biggest andalusite**-** it will show the best inclusion trails.

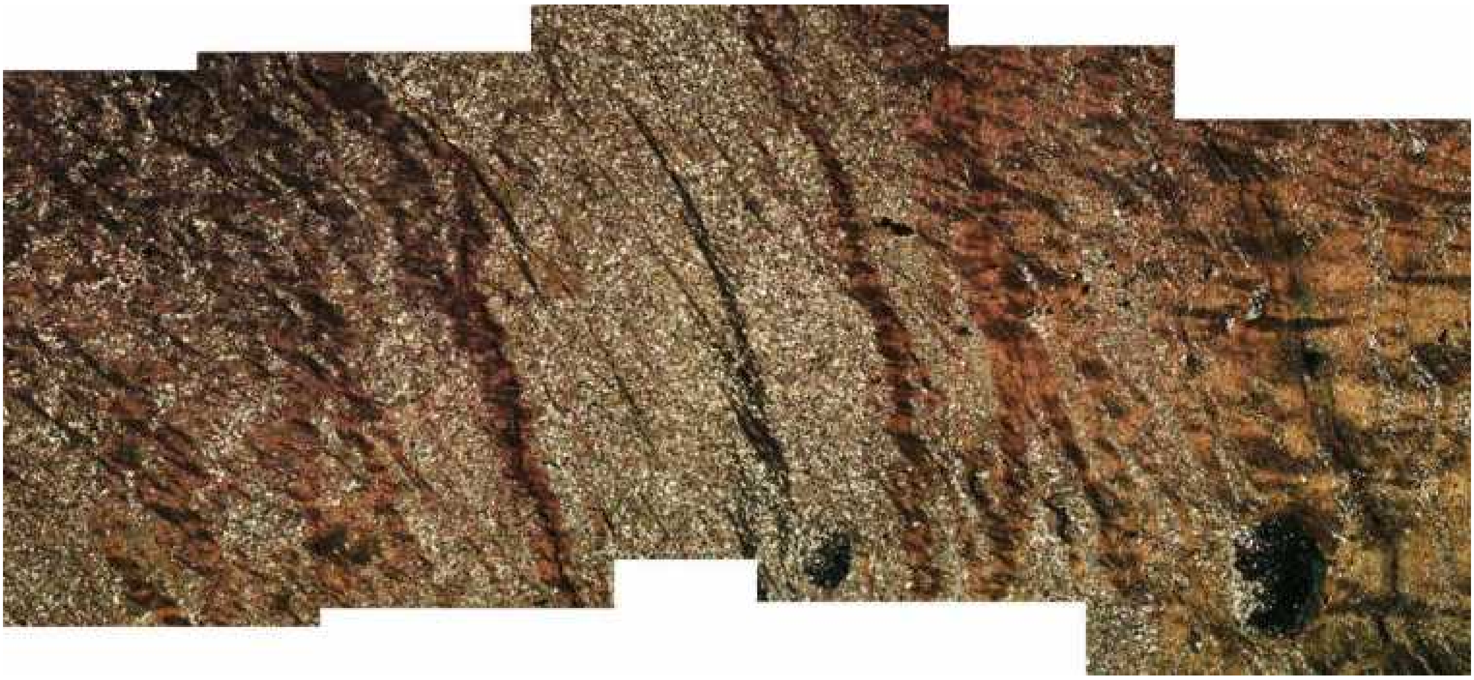


- When did these andalusites grow relative to the foliations?

RJS90436. This is a quartz-muscovite-biotite-sillimanite schist, with minor zircons. The main fabric of the rock is made up of an anastomosing foliation cut by shear bands, which on the large scale show a fairly consistent asymmetry. The zircons cannot be identified directly, however the dark radiation damage haloes in the biotites are characteristic of this Uranium rich mineral.

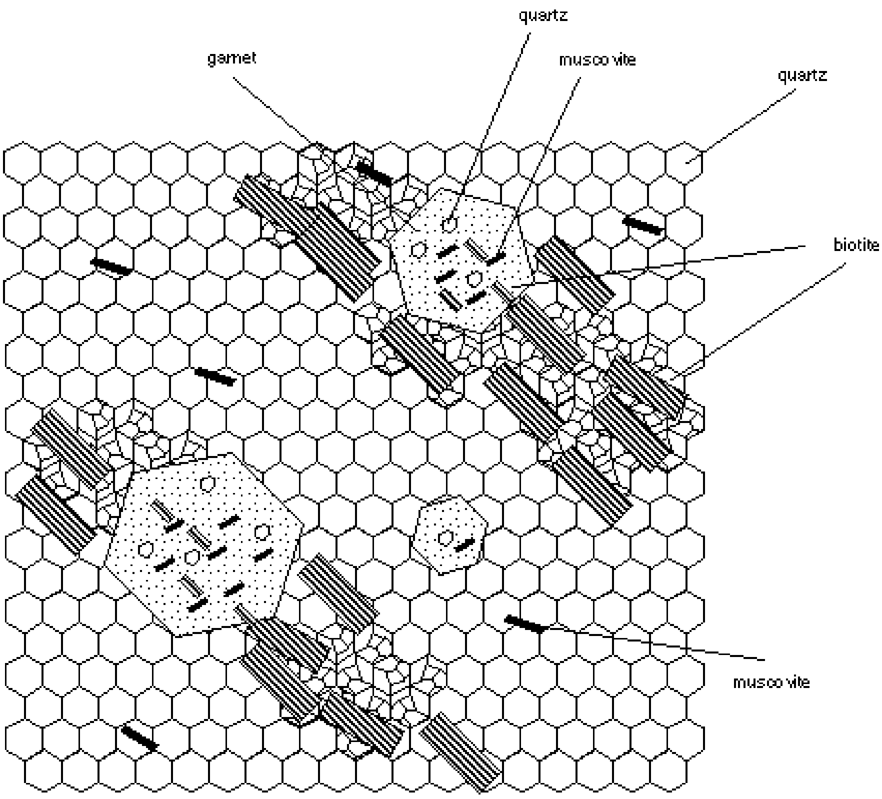


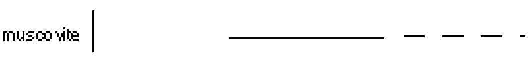
RLA-1A Quartz-muscovite-biotite-chlorite-garnet schist. This thin section is a higher grade example of the crenulations you saw in the Lake Glenmaggie slide, and preserves evidence of several stages of deformation in the porphyroblast inclusion trails. The overview picture taken with cross polars is about 1.5 across, and the enlargement shows the large grain in the lower right of the image in plain and cross polarised light.

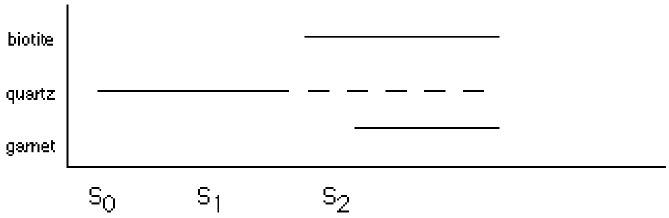


- Make a sketch showing the angular relationships between the foliations that have been preserved in this rock. Draw a chart showing the age relationships between deformation and mineral growth, recrystallisation and alteration.
- Construct a chart showing the timing of mineral growth relative to deformation, for white mica and all the porphyroblast minerals (including the opaque needles).

Example Timing Chart





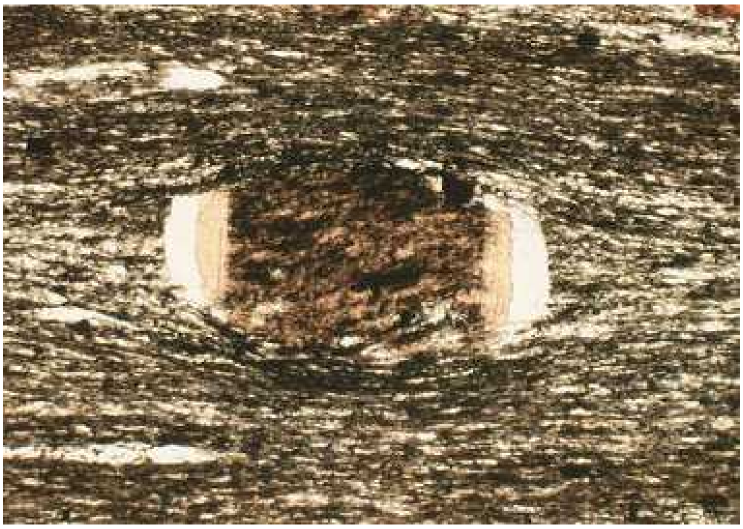


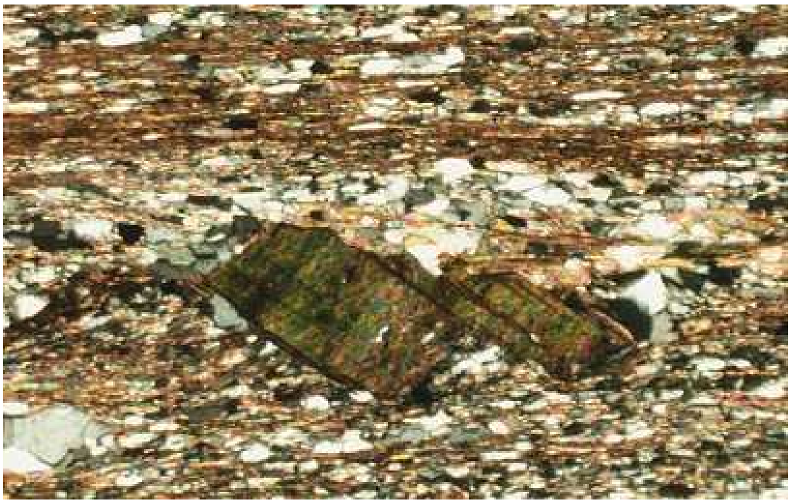
4) Shear zones and kinematic indicators in naturally deformed rocks.

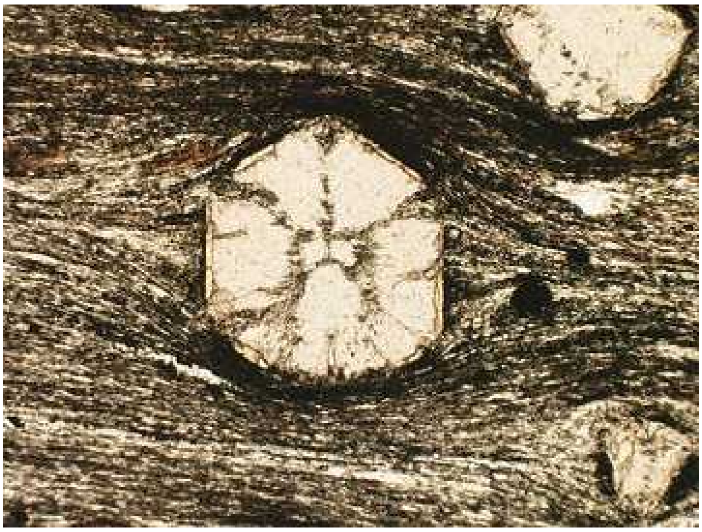
S-C Mylonite. This rock is a superb example of a type II S-C mylonite. C-planes are defined by thin mica-rich seams, with occasional mica "fish" which have been sheared to produce asymmetric shapes that indicate the sense of shear, which matches the sense of shear indicated by the S-planes defined by the quartz grain shape preferred orientation. Note that the dynamic recrystallisation has reached an equilibrium with the straining such that the preferred orientation of grain shapes does not in any way reflect the finite strain. Put the gypsum plate in to see the very strong but domainal preferred orientation of lattice planes in the quartz.

- Make a sketch of the S-C fabric, and label the kinematic (sense of shear) indicators.

257 Quartz-muscovite-biotite-graphite-garnet schist. This thin section shows a number of beautiful metamorphic and deformation microstructures, including pressure shadows around porphyroblasts (rare at these temperatures), zoned inclusions, inclusion trails. The first image shows an overview and the subsequent images show enlargements from the same slide.







- Describe the deformation/metamorphic history of this masterpiece of complexity.

Lab 5A-Vein & stylolite movies

VIEPS/Mainz Microstructure Course

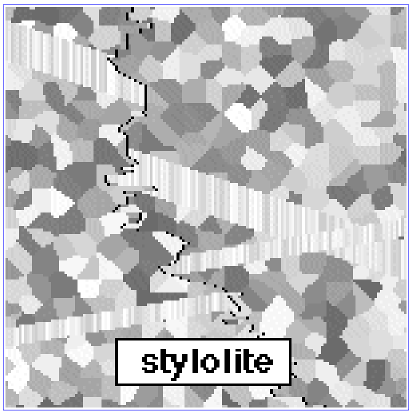
1) Different vein types

Lecture 5.b deals with the various types of veins and their internal structures. It also contains a few movies that show the development of the vein types over time.

- Look up and read through lecture 5.b and watch the movies until you think you understand the differences between the various types well enough.
- Which vein types can give you the correct opening trajectory (provided the crystals are tracking 100%)?
- Why is it important to know of which type a vein is (say antitaxial or syntaxial) if you want to know the opening trajectory?

Look up movies in lecture 5.b

2) Stylolite movie



This is the movie of a developing stylolite that you can also find in lecture 5.b. Play the movie and answer the following questions:

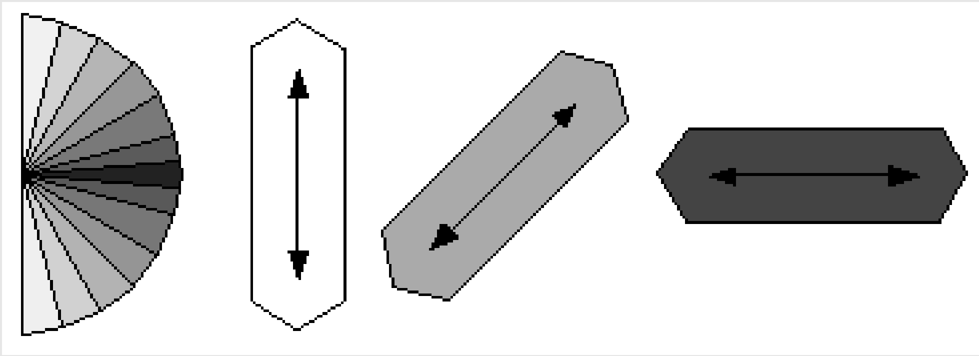
- What is the relation between the direction in which the stylolite "teeth" point and the shortening direction?
- Two older veins are off-set by the stylolite. Explain the difference between these off-sets and those caused by a (small) shear zone. How would you distinguish between the two?

(3) Computer simulation of crack-seal growth

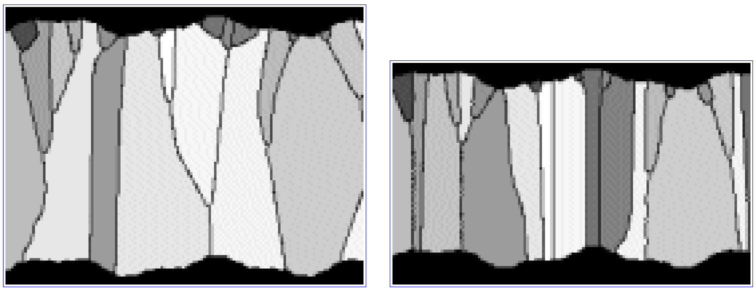
Four movies were made with a 2-dimensional computer model that simulates the growth of a vein by the crack-seal mechanism. The movies show how several factors play a role in determining the shape and orientation of crystals in a vein:

- crystallographic orientation
- growth anisotropy of crystals

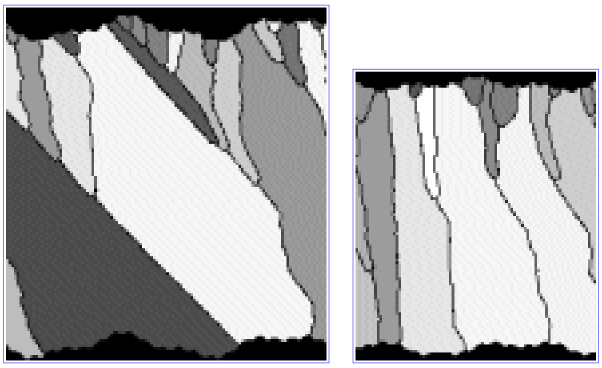
- magnitude and direction of opening increment per crack-event
- shape of crack



The movies show repeated cracking and sealing on one side of a vein crystals subsequently filling (sealing) the crack from one side only. This is thus an asymmetric vein, but can also be regarded as one side of an antitaxial vein. The "mineral' that fills the vein is somewhat like quartz. It has one fast growth direction (// to C-axis) and would, if allowed to grow in free space, grow into a shape as shown in the picture. Each crystal is shaded grey according to the orientation of its C-axis. Horizontal C-axes are dark and vertical ones are white.



Movies A&B



Movies C&D

Watch the four movies and then answer the following questions

- Describe the internal structures in the 4 veins (grain shape, orientation, etc.)
- Does a crystallographic preferred orientation develop, and if so, which? (are there certain "winners" and "losers"?)
- What is the opening trajectory in each case and how much of it is reflected in the shape of the grains?
- Can you relate your observations to the 4 factors listed above that may determine the internal structure in the veins?

Continue with part (B) of this lab.

Lab 5B-Thin sections of veins

VIEPS/Mainz Microstructure Course

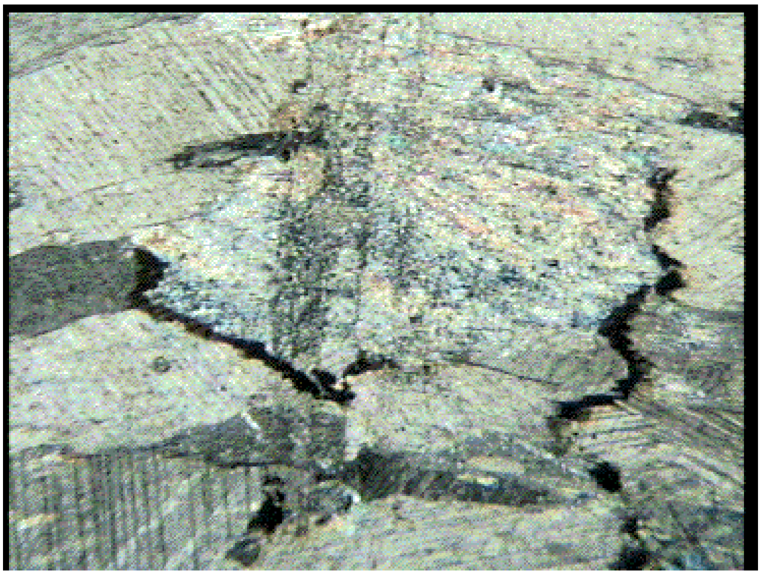
(4) Thin sections of veins

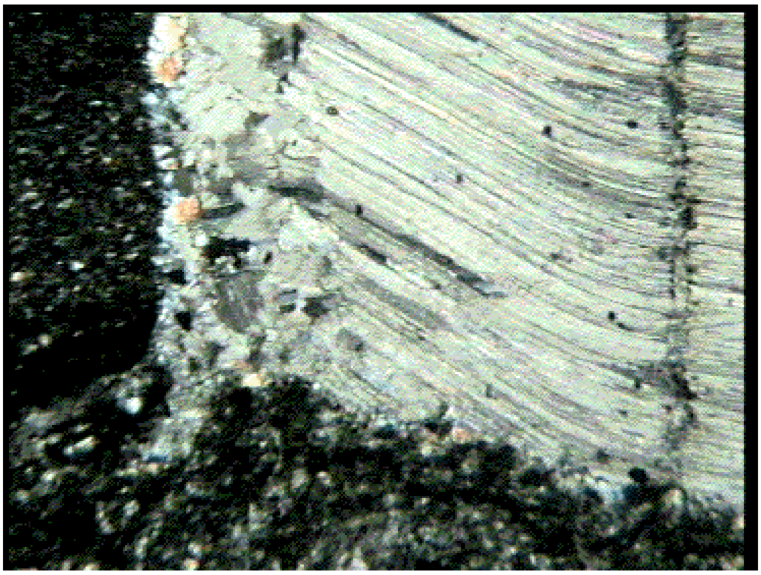
The thin sections show a variety of structures that have been discussed in the lecture. Have a look at them and answer the following questions:

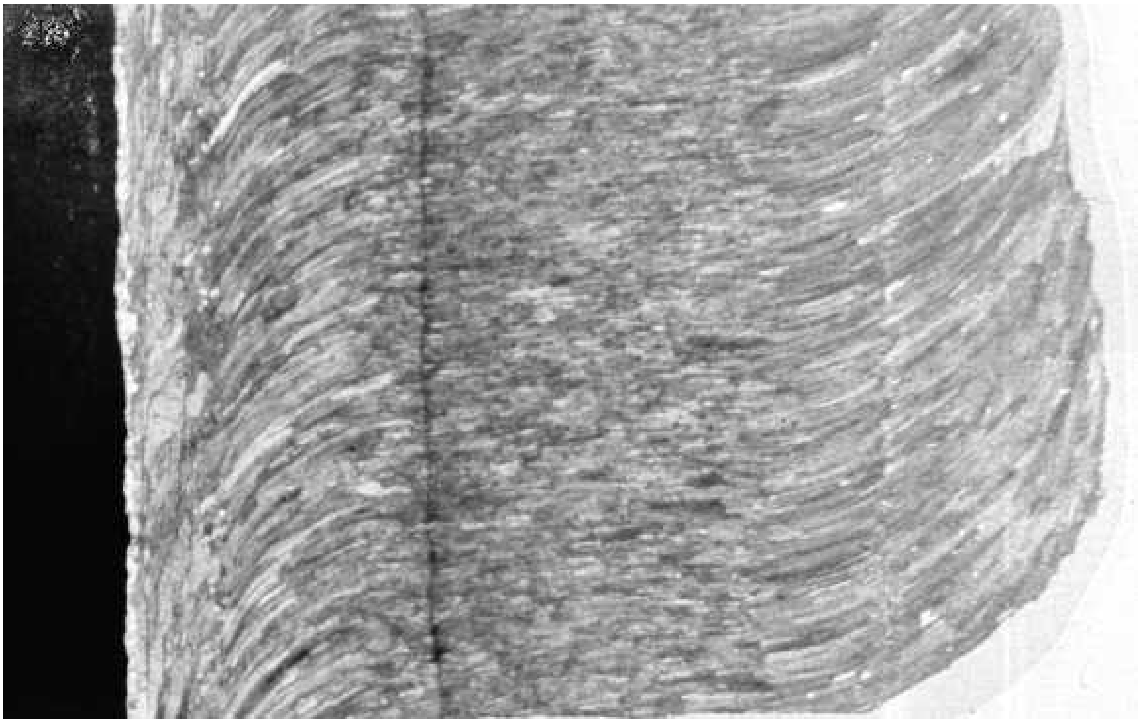
- What is the grain shape (e.g. fibrous, elongate-blocky, etc.)
- What is the vein type (e.g. antitaxial, syntaxial, etc.)
- What can you say about the opening history of the veins (opening trajectory, propagation, etc)
- Are there any other microstructures that relate to veins and dissolution-precipitation processes

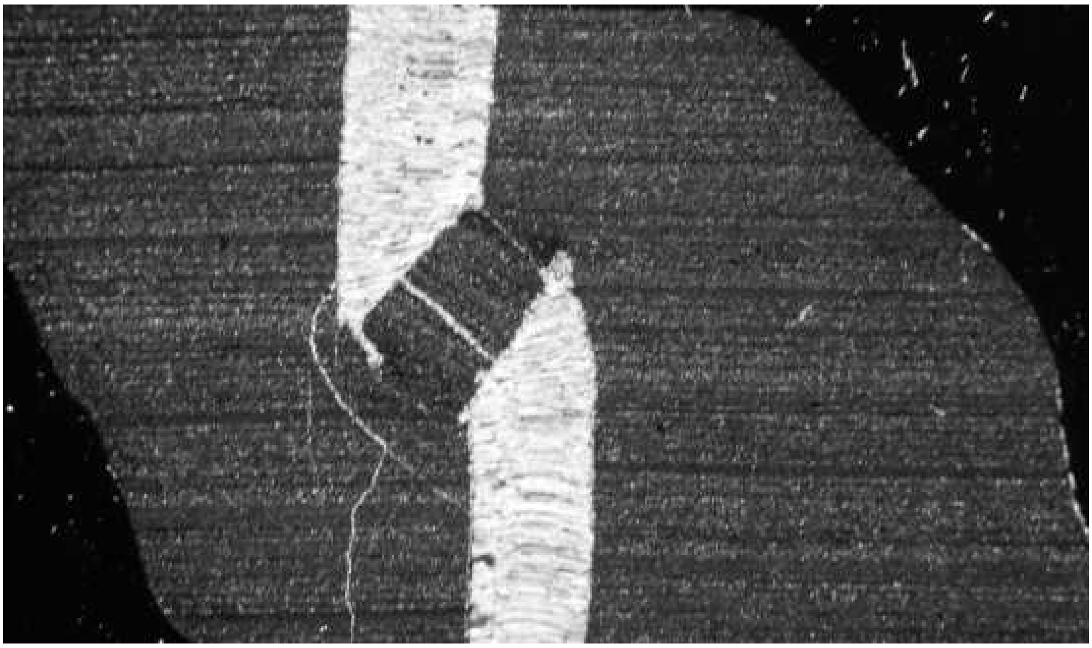
In short: **What can you see and what does that tell you about what happened?**

Group 1: Calcite veins from dolomitic shales near Arkaroola (SA). Several of these images are courtesy of Michelle Robinson, who completed her Honours degree on these rocks. Some of the thin sections show the tip of veins, with complex structures around it (as shown here).



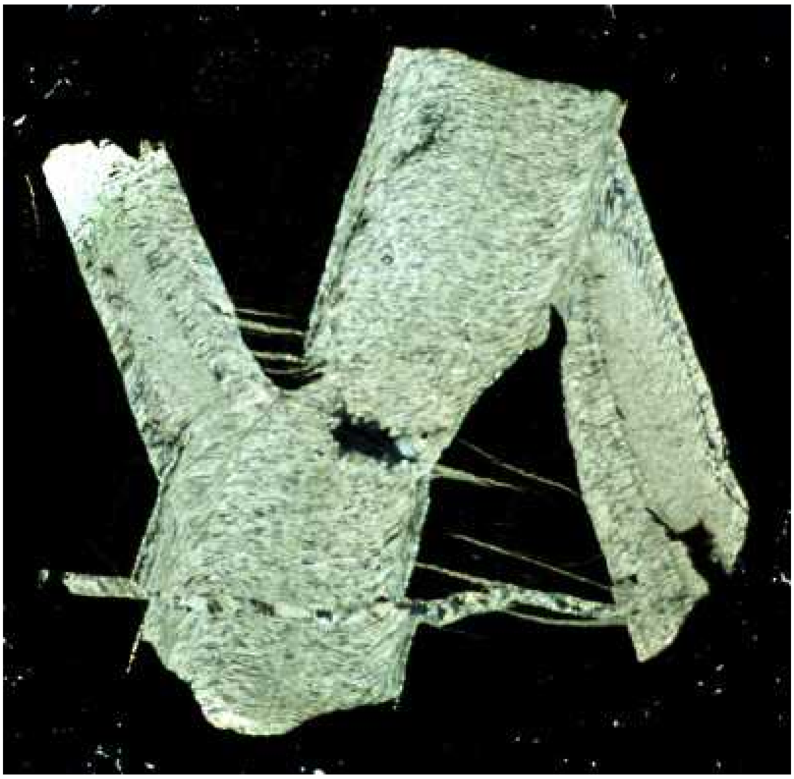






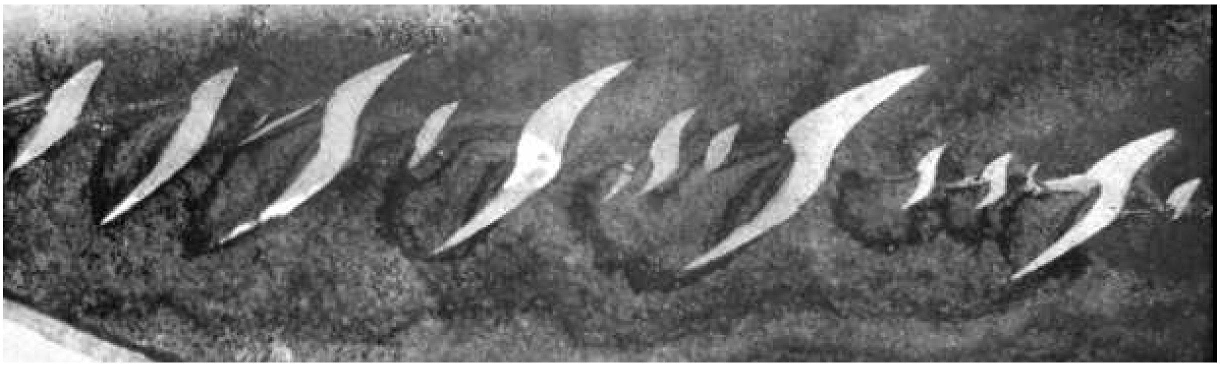
Larger apparent crosscutting vein structure with smaller actual crosscutting structure. Mostly fibrous calcite, with minor blocky calcite and quartz is present. Cross polarised light, field of view of overview is 4 cm.

- What are the vein age relationships (e.g. antitaxial, syntaxial, etc.)



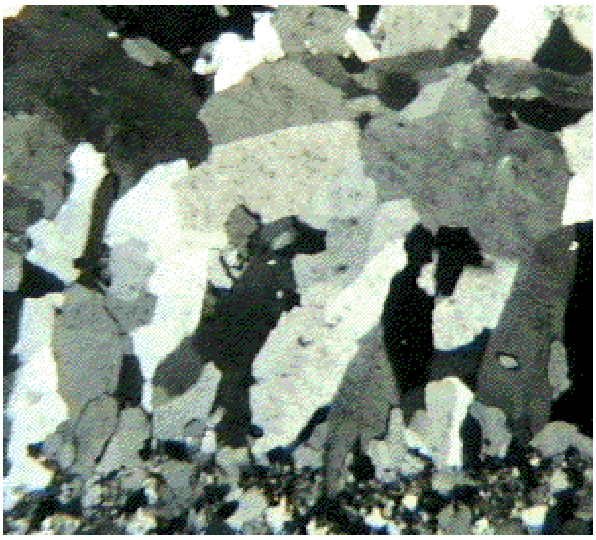
En echelon vein structures in the field (horizontal field of view 40cm) and in thin section (horizontal field of view 7.5cm).

- What is the sense of displacement in each image.



Highly disrupted vein network formed between two faults (oriented about 15 degrees clockwise from vertical) with bedding in shale bent by faults.

Group 2: Several mainly quartz bearing veins from Poolamacca, Victoria and Arkaroola. The Arkaroola ones also contain anatase (Ti-mineral), with pretty structures to have a look at.



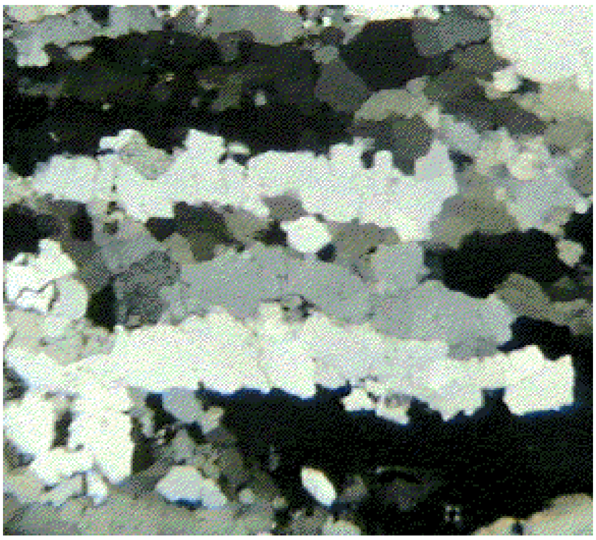


Table of Deformation Mechanisms and Processes

VIEPS/Mainz Microstructure Course

NAME OF PROCESS(P) OR MECHANISM (M)	ATOMIC SCALE PROCESS	DIAGNOSTIC MICRO-STRUCTURES	Grain Shape Foliation	Crystallographic Preferred Orientation	RHEOLOGICAL IMPLICATIONS	COMMON MINERALS
Fracturing (M)	Breaking of inter-atomic bonds	Gouge, breccias, boudinaged grains	+ve or -ve	-ve (ie negative, is weakened by this mechanism)		Any, more at high stress & low T
Frictional Sliding (M)	Frictional sliding on surfaces	Gouges, breccias, pseudotachylites, domino grains	+ve or -ve	-ve	$\tau \propto \sigma$	Any, more at high stress & low T
Diffusional Creep (M)	Diffusional movement of vacancies and interstitials	New crystal void of pre-existing impurities (hard to prove in nature)	+ve	?	$\dot{\varepsilon} \propto \frac{\sigma}{d^2}$ (Nabarro-Herring) or $\dot{\varepsilon} \propto \frac{\sigma}{d^3}$ (Coble creep)	Any, more at low stress & high T
Dislocation Glide (M)	Re-arrangement of inter-atomic bonds	Deformation lamellae, deformation bands, undulose extinction	+ve	++ve	$\dot{\varepsilon} \propto \sigma^3$ also a hardening with finer grain size (Hall-Petch Law)	Any, more at low stress & high T
Twinning (M)	Re-arrangement of inter-atomic bonds and re-orientation of lattice site	Twins (sharp nosed, narrow, parallel to rational twin planes)	+ve	+ve		Calcite especially at low T and low strain, plagioclase, quartz (but not visible), amphiboles
Kinking (M)	Dislocation glide on single slip system	Kink bands	+ve	+ve		Micas, low T quartz, kyanite

Grain Boundary Migration (P or M)	Atomic scale diffusional processes, possibly involving dissolution and precipitation	Irregular grain boundaries, pinning microstructures, orientation families, Lattice preferred orientations with strong point maxima, non-120°-triple junctions	+ve or -ve	+ve	Produces low dislocation density material Q softer	Any, more at high T, especially quartz, olivine, fsp
Rotation Recrystallisation (P)	Progressive addition of dislocations of same sign to sub-grain wall	Mortar texture or core and mantle texture, bi-modal grain size	-ve	-ve	Change in grain size can strengthen or weaken material	Any, more at low stress & high T, especially quartz, fsp, olivine
Recovery (P)	Climb, mutual annihilation of dislocations of opposite signs, formation of subgrain walls	Polygonisation, foam textures, 120°-triple junctions	-ve	+ve or -ve	Produces low dislocation density material Q softer	Any, more at high T
Climb (M)	Diffusional addition or removal of atoms at dislocation line		+ve	0		Any, more at high T
Lattice Rotation (P)	Dislocation glide and/or bulk rotation of grains	Crystallographic preferred orientations	0	+ve	Well developed fabrics may be stronger or weaker than random fabrics	Any, more at low stress & high T
Bulk Rotation (M or P)	Physical rotation of whole or part of mineral grains	Helical inclusion trails, bending of crystals, delta & sigma porphyroclasts	+ve	+ve or -ve		Any
Grain Boundary Sliding (M)	Dislocation movement on "clean" grain boundaries, shearing on "dirty" ones		0	0		Any
Diffusive Mass Transfer (M or P)	"Long range" diffusion of atoms	Veins, pressure shadows, porhyroblasts	+ve or -ve	+ve		Any, especially quartz and calcite

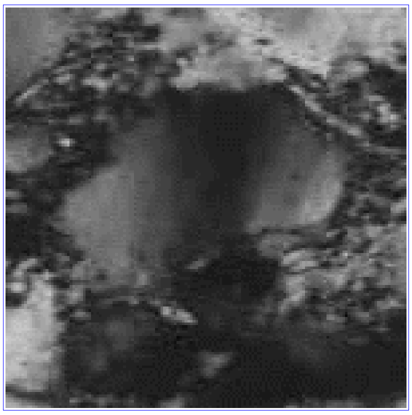
Phase Change (M or P)	Changed crystal structure without change in bulk chemistry of mins	Phase boundaries in minerals	?	?	Often associated with volume change	Quartz, calcite-aragonite, olivine

Illustrated Glossary- Lecture 1

VIEPS/Mainz Microstructure Course

undulose extinction

wavy extinction, common in quartz and calcite, due to plastic strain. The crystal lattice is actually bent, so that when the microscope stage is rotated, one or more bands of extinction with gradational boundaries will sweep across the grain. Shows that the crystal is full of a distributed cloud dislocations. Common in quartz calcite.

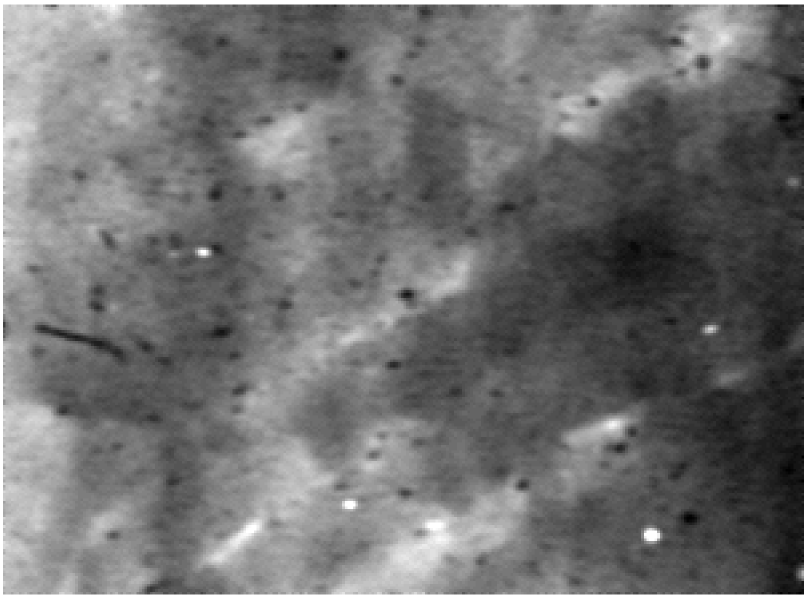


sharp extinction

single orientation of extinction across whole grain, implies low density of dislocations

deformation bands

distinct bands of different extinction that are obviously part of the same crystal. a more localised form of undulose extinction where some concentration of dislocation has taken place. In picture below they trend NE-SW



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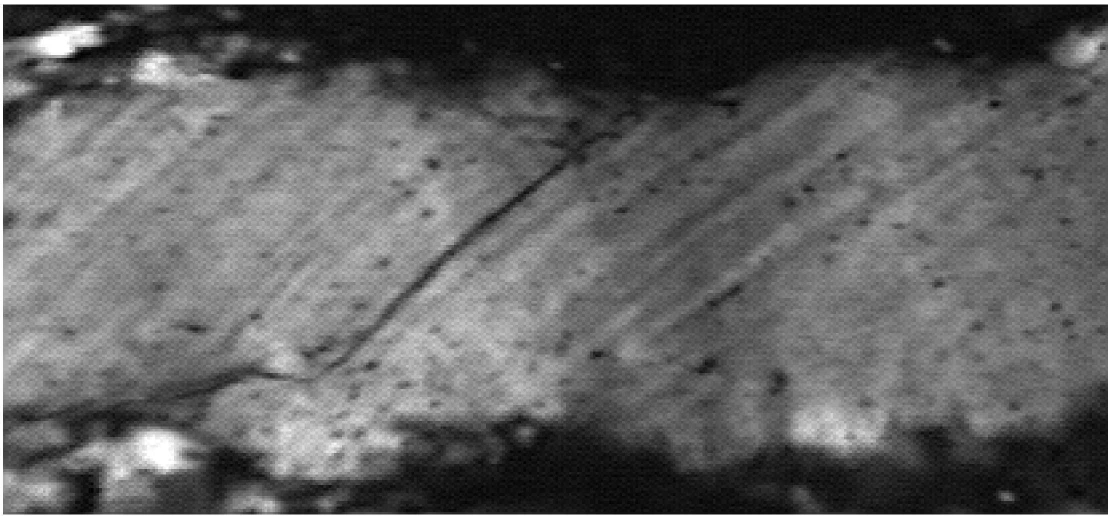
deformation lamellae

sharp sided, narrow and repeating bands usually forming sub-parallel to a specific crystallographic orientation, such as the basal plane in quartz. can be due to a number of processes, but are commonly zones of concentrated slip on a given slip system. In picture below they trend NE-SW



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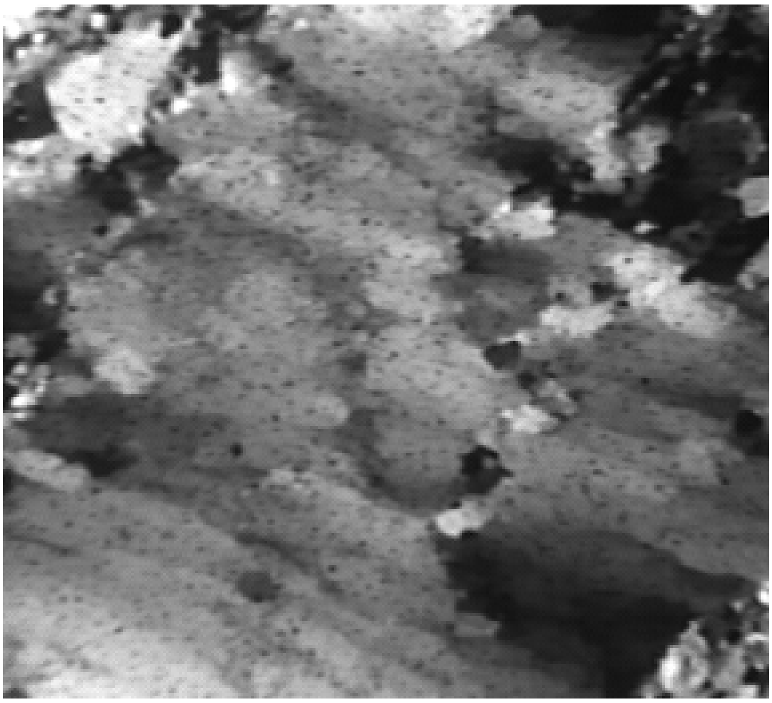
subgrain

small regions within a grain with uniform extinction, but clearly related to other subgrains in orientation, which together make up a whole grain. The misorientation sufficient to declare that two regions are still subgrains is to say that the misorientation is less than 7 degrees, but this is impossible to measure using a standard microscope and stage. Forms by migration and accumulation of dislocations with the same sign. Often concentrated at grain edges at low temperatures.



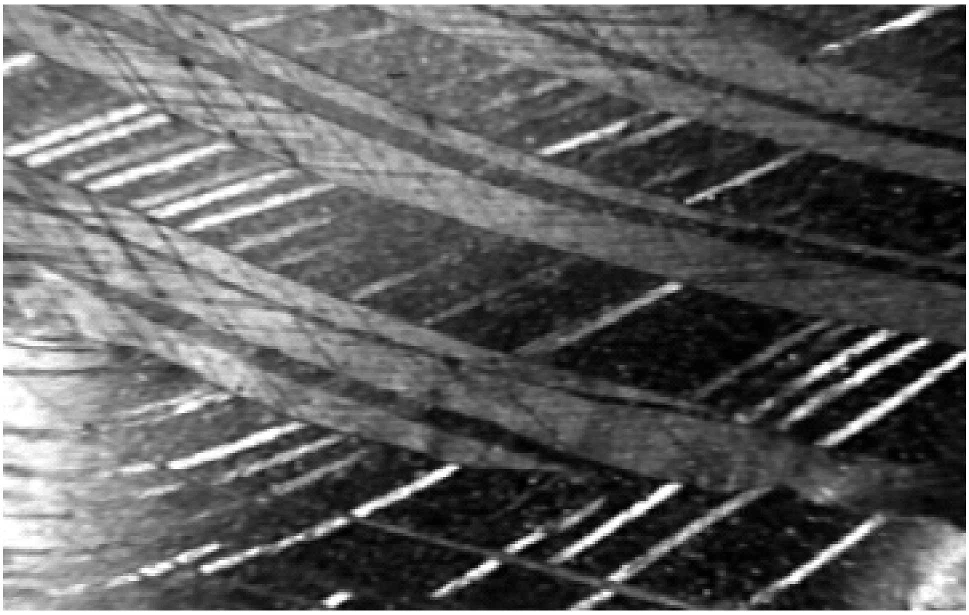
defects

imperfections in a crystal lattice. include point, line and plane defects. Abundant in all natural crystals.

Kink bands Parallel sided zone of differently oriented crystal within a single grain, with no special "twin orientation" between zone and host crystal. Often form by either by a polygonization process where a gently curved crystal resolves itself into several low defect bands separated by tilt wall boundaries, or by a gradual rotation and growth of the zone from a small elongate nucleus. The former are common in high temperature olivine, the latter in micas & kyanites.

twins

parallel sided zone of differently oriented crystal within a single grain, with special "twin orientation" between zone and host crystal. The amount of strain undergone during the passage of a twin boundary is fixed, and no further twin related strain takes place once a twin has passed a particular point. Very common in deformed calcite and plagioclase.



VIEPS Deformation Microstructures Course Lab 1 - Deformation Mechanisms

Illustrated Glossary- Lecture 2

grain boundary migration

The movement of grain boundaries resulting from the diffusion of atoms or atom clusters from one crystal to its neighbour.

rotation recrystallisation

also known as the progressive misorientation of subgrains. The formation sub-grains by the relative rotation of part of a crystal lattice with respect to its neighbour.

static recrystallisation

the formation and movement of subgrain and grain boundaries unrelated to deformation. Generally as a result of a raising of the temperature. Driving force is reduction in grain boundary energy.

dynamic recrystallisation

the formation and movement of subgrain and grain boundaries during deformation. Driving force is dislocation energy, chemical energy, reduction in grain boundary energy.

meta-dynamic recrystallisation

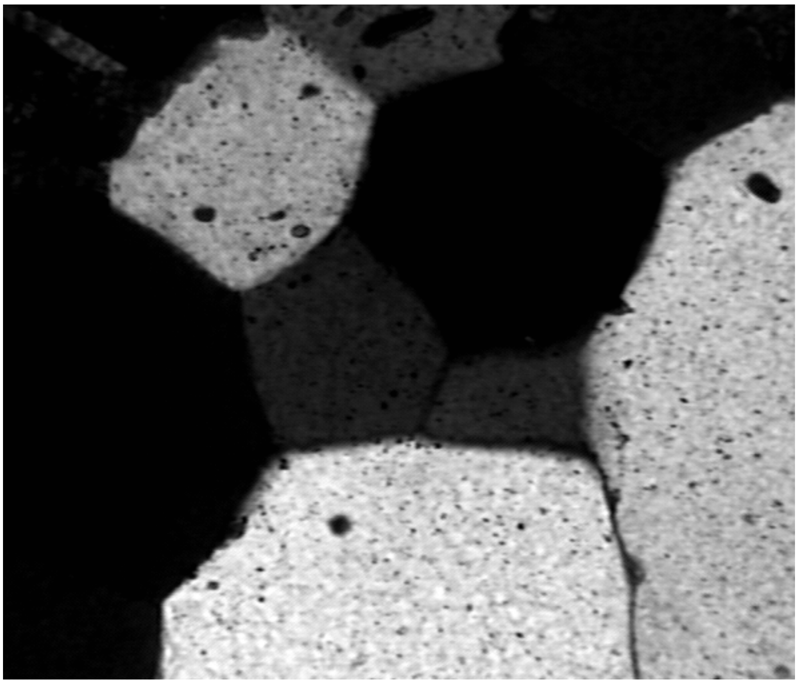
the formation and movement of subgrain and grain boundaries driven by but subsequent to deformation. Driving force is dislocation energy, chemical energy, reduction in grain boundary energy.

Illustrated Glossary- Lecture 3

VIEPS/Mainz Microstructure Course

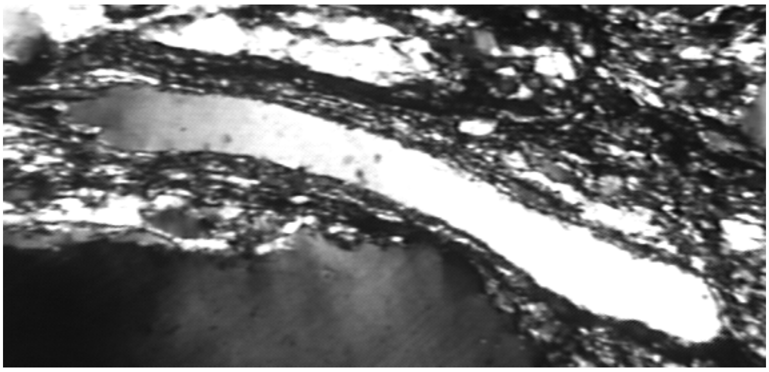
foam texture

grain boundary geometry where triple junctions meet close to 120 degrees and all grain boundaries are straight or gently curved. IF IN THE EXAM YOU STATE THAT A PARTICULAR MICROSTRUCTURE SHOWS TRIPLE JUNCTIONS YOU WILL FAIL, HOWEVER IF YOU SAY THAT THE TRIPLE JUNCTIONS ARE AT 120 degrees OR SOME OTHER ANGLE, YOU MAY PASS.



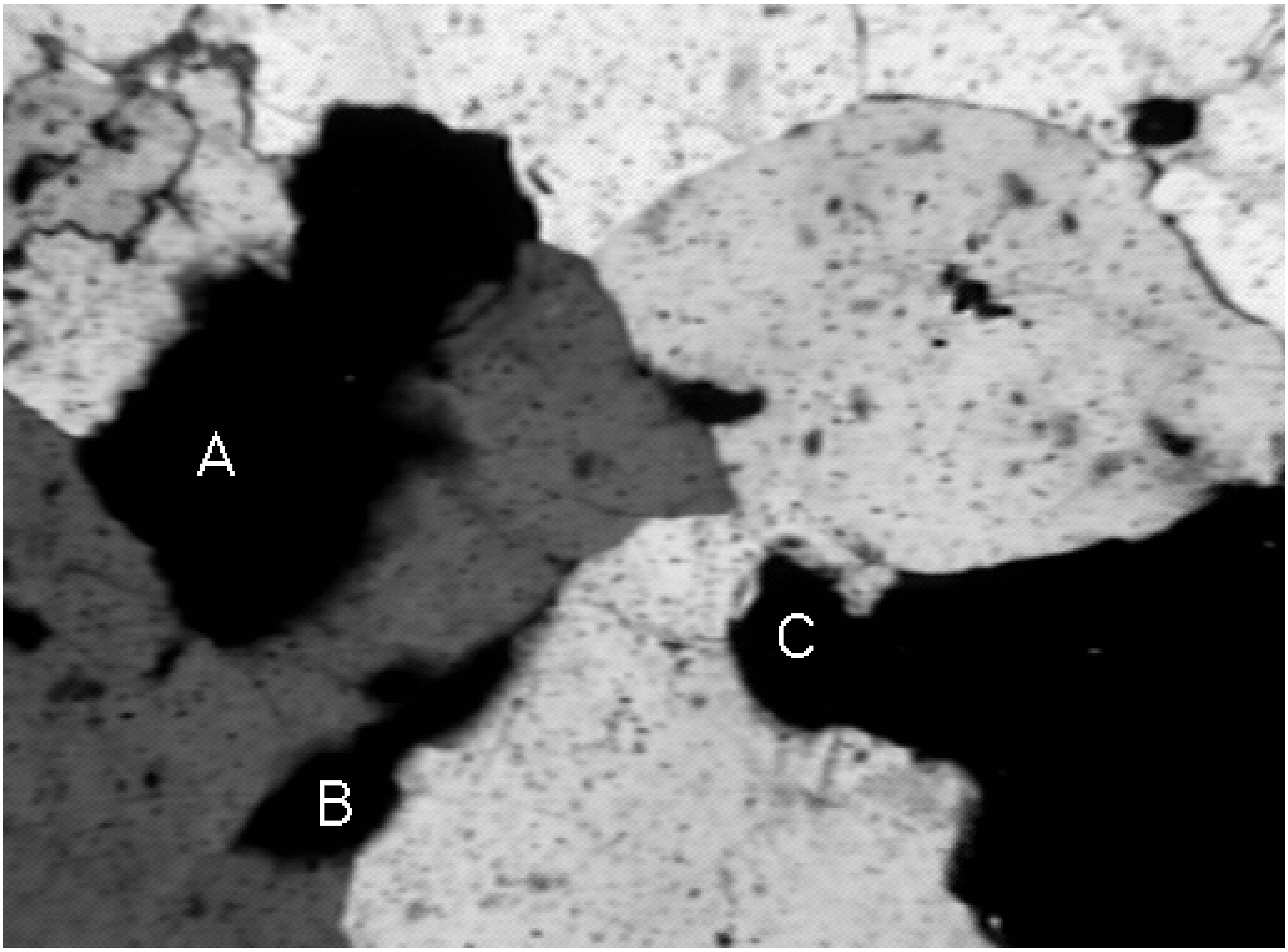
ribbons grains

showing large aspect ratios sitting in a finer grained, more equant matrix of same mineralogy. Can form by flattening of individual grains, grain boundary migration, coalescence of two grains with same orientation, or rotation of neighbouring grain's lattices into same orientation.



orientation family

isolated (in 2D) set of grains with the same crystallographic orientation which were once part of same grain, but have been isolated by grain boundary migration. Grains A, B & C below all have the same crystallographic orientation mortar texture rock showing bimodal grain size distribution with large grains surrounded by a matrix of smaller grains.



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cleavage

originally old mining term meaning that the rock can be cleaved, ie it can be split into planar sheets, used for roofing tiles. The two most common types of cleavage are slaty cleavage and crenulation cleavage.

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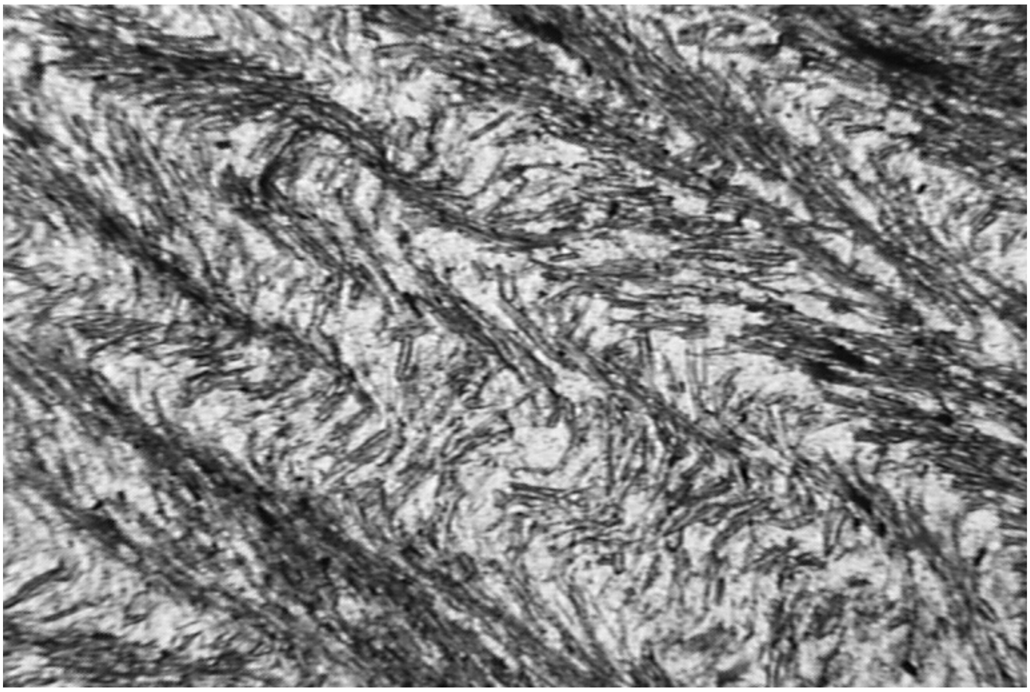
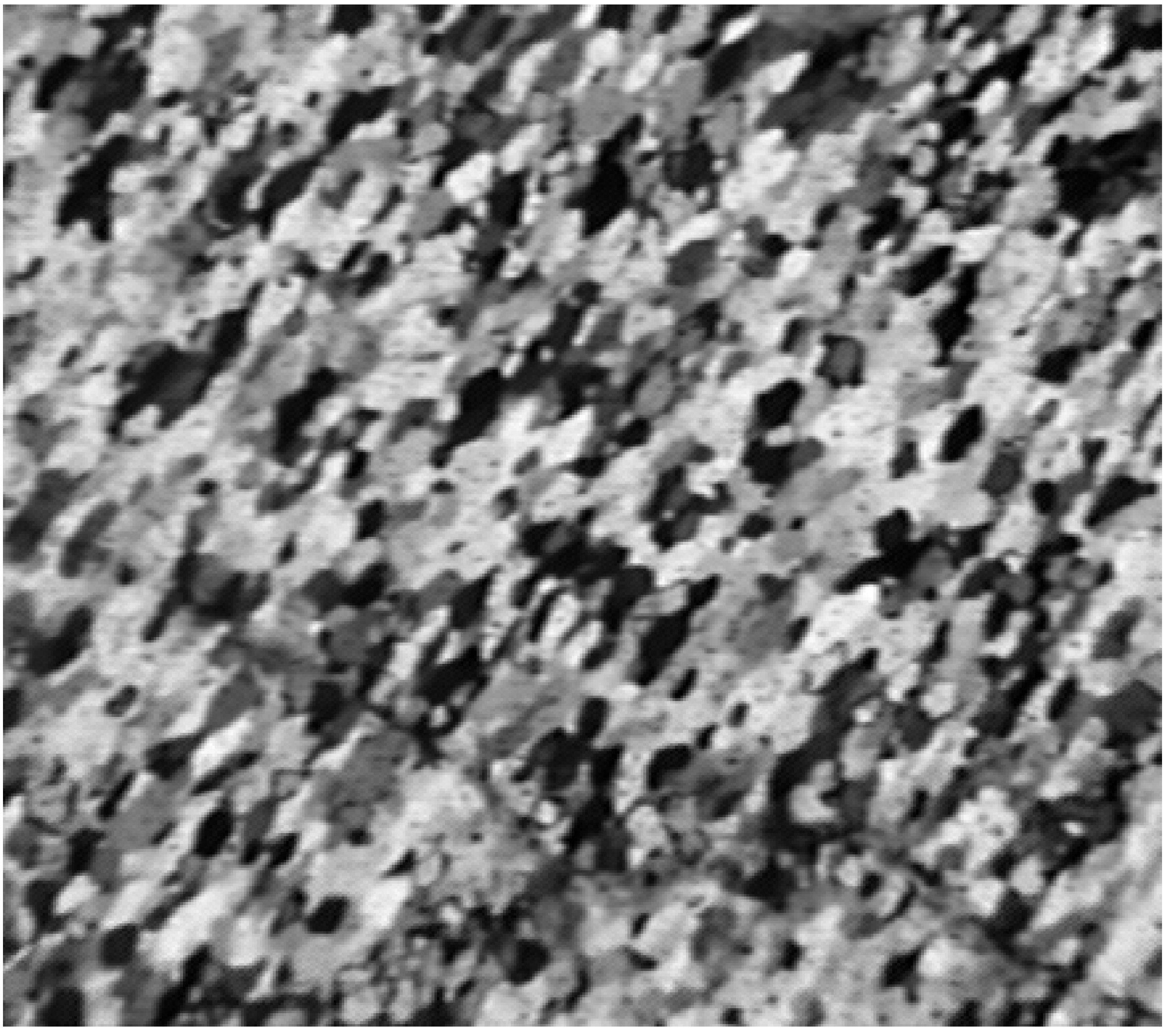
crenulation cleavage

cleavage formed by reorientation of a previous cleavage. Occurs by a combination of micro-buckling, recrystallisation & mass transfer.



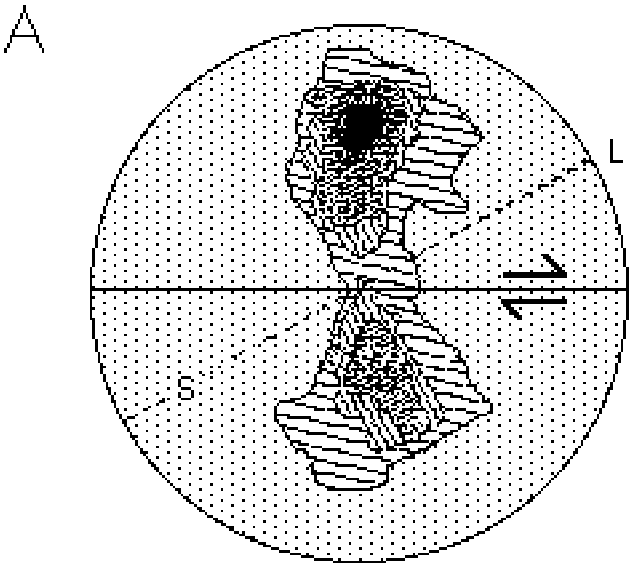
GSF Grain Shape Foliation.

The preferred shape orientation distribution of grains in a rock.
Grain boundary alignment: The preferred alignment of grain boundaries in a rock, which does not necessarily directly correlate with GSF.



CPO Crystallographic Preferred Orientation.

aka Lattice Preferred Orientation, texture, fabric, Orientation Distribution Function. The orientation distribution of one or more crystal axes in a rock.
Girdle: small or large circle distribution of crystal axes on a stereonet.
Point maxima: cluster of crystal axes around one orientation.



Brunel, 1980

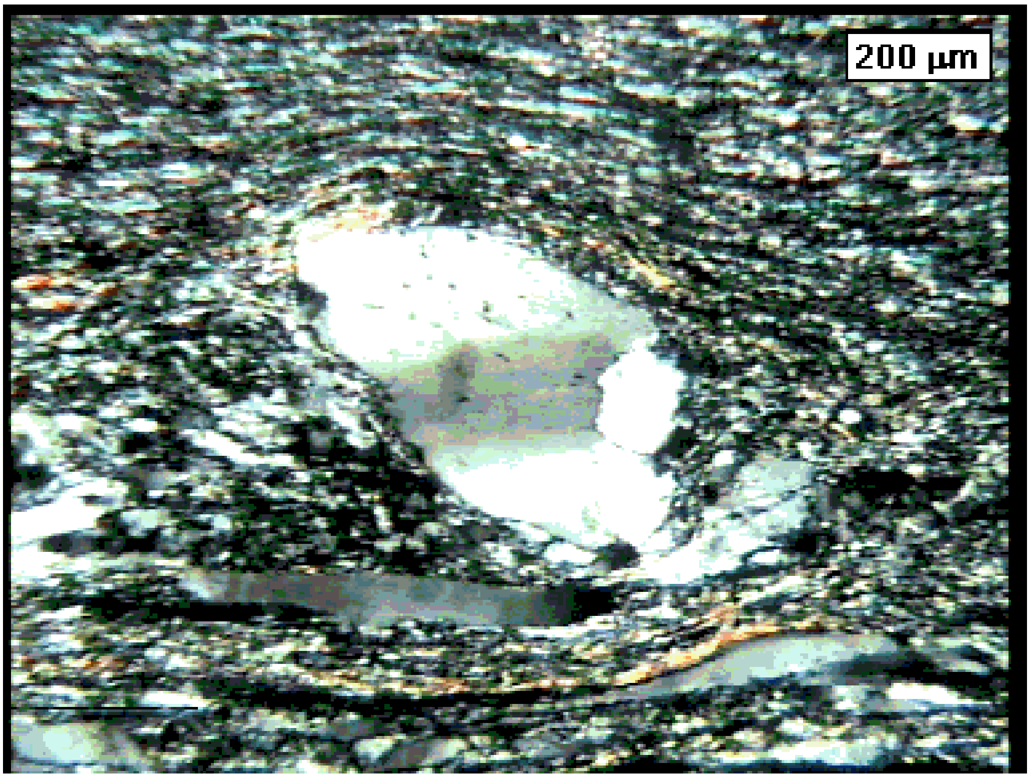
VIEPS Deformation Microstructures Course Lab 2 - Grain shape and crystallographic fabrics

Illustrated Glossary- 4

VIEPS/Mainz Microstructure Course

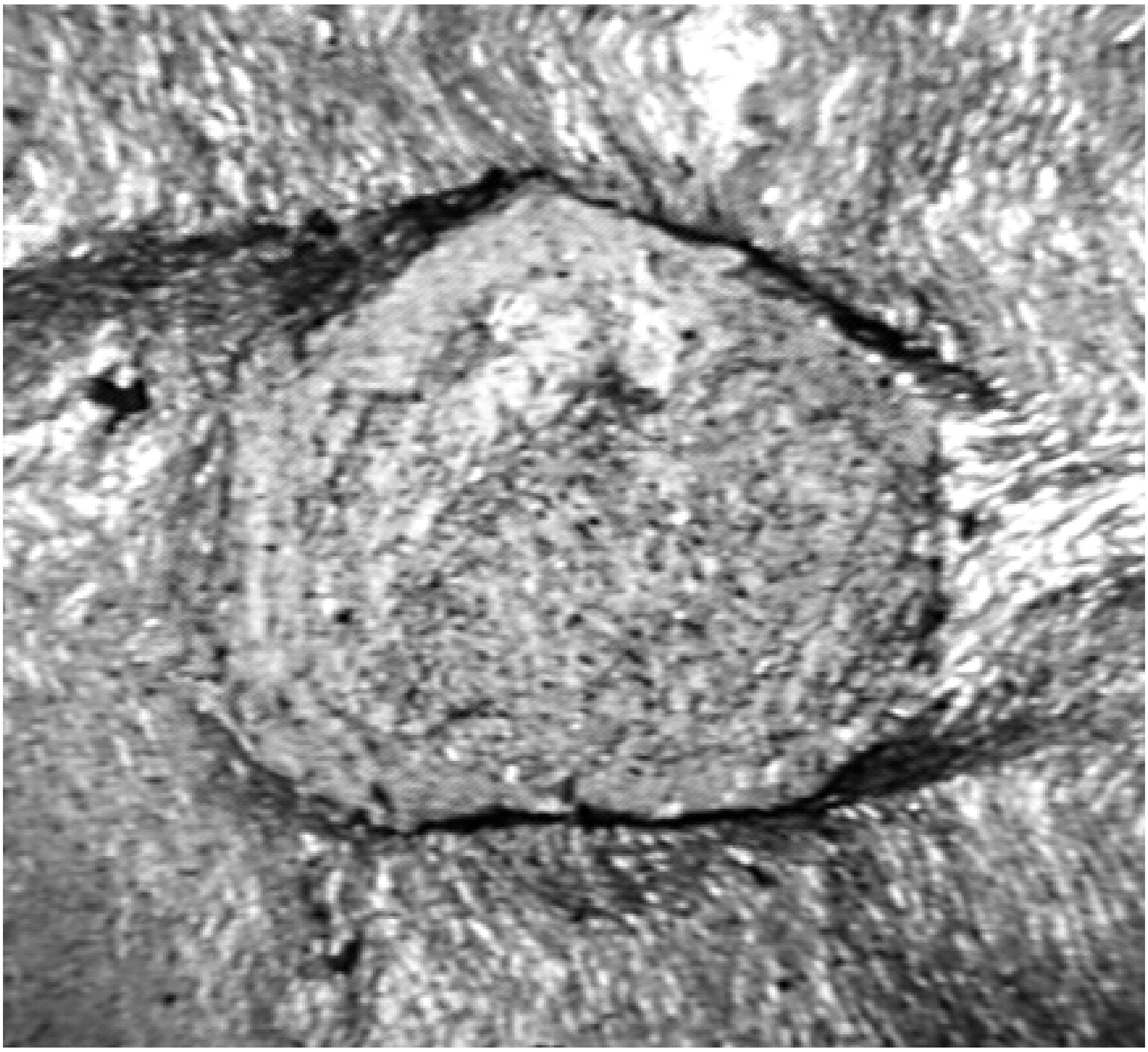
porphyroclast

grain considerably larger than the matrix which is a relict of an earlier grain size



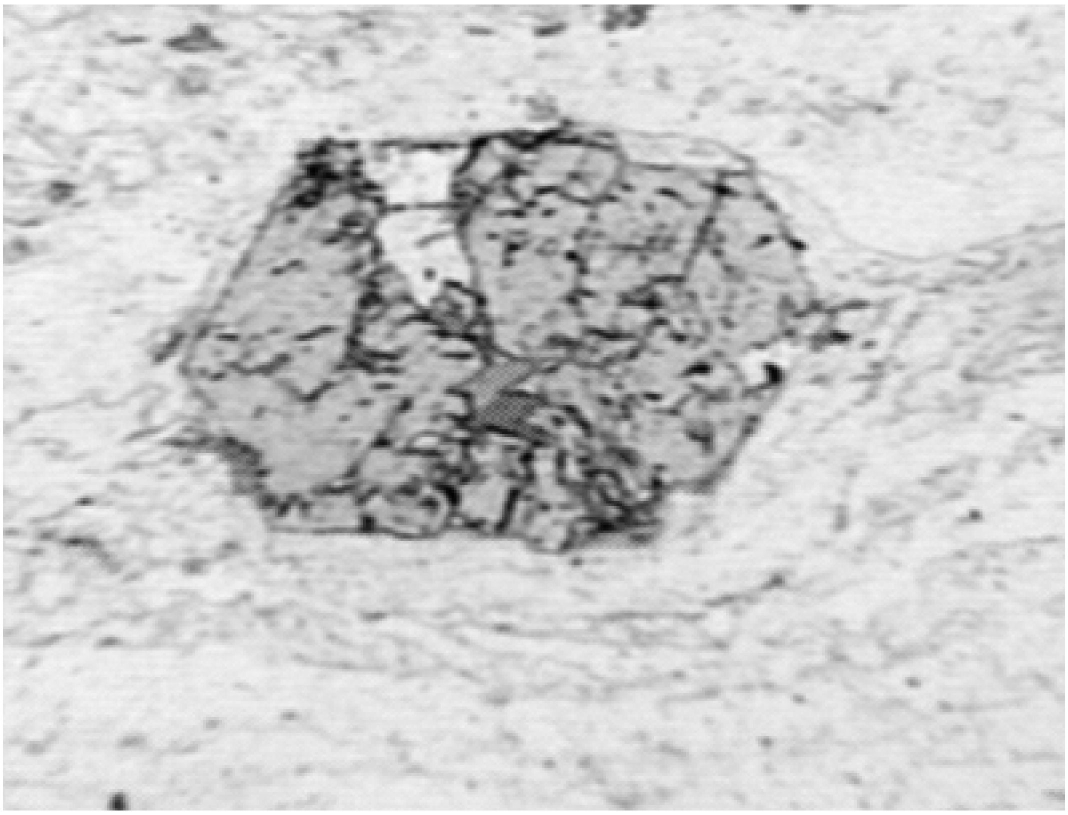
porphyroblast

Grain formed during metamorphic growth which is considerably larger than the matrix



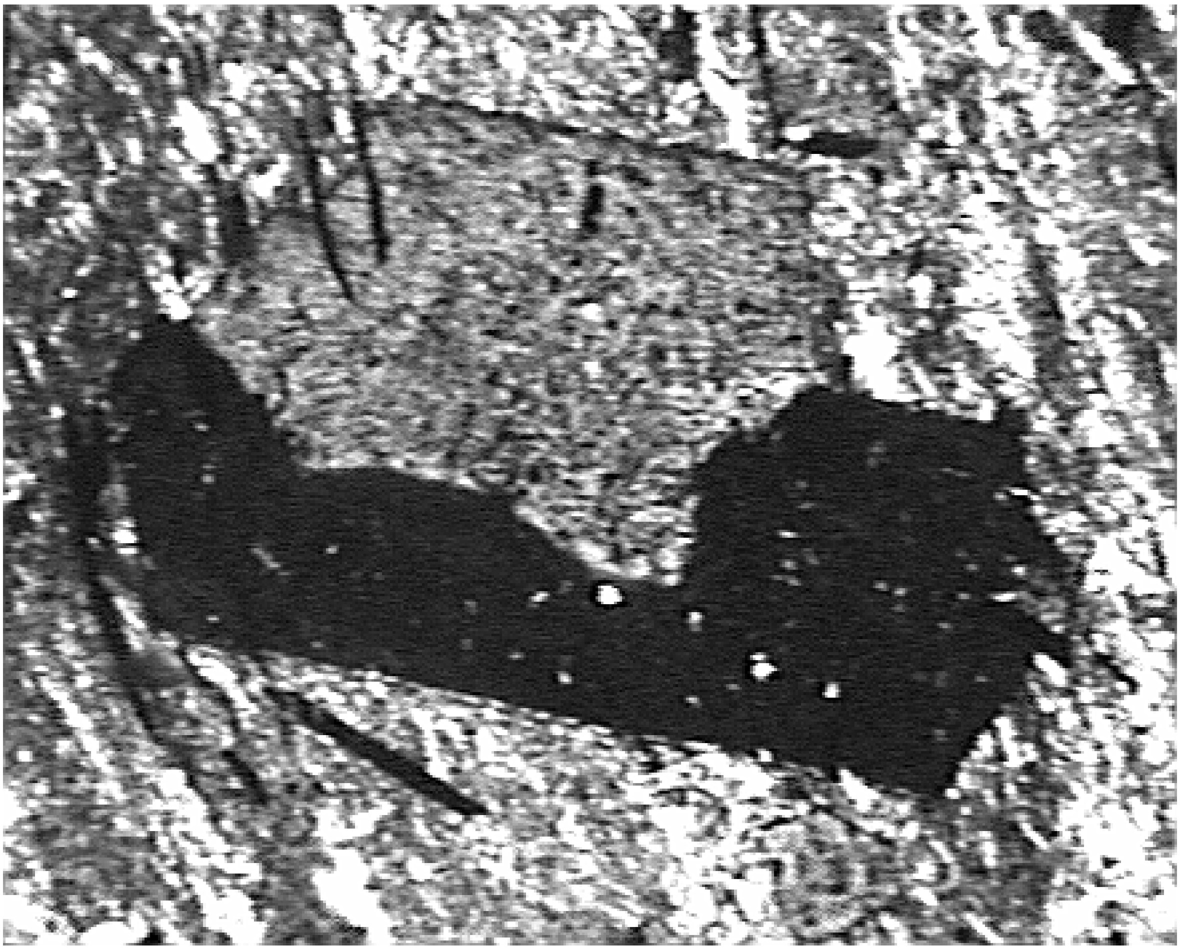
idioblastic

porphyroblast which has grain boundaries controlled by its own crystallography



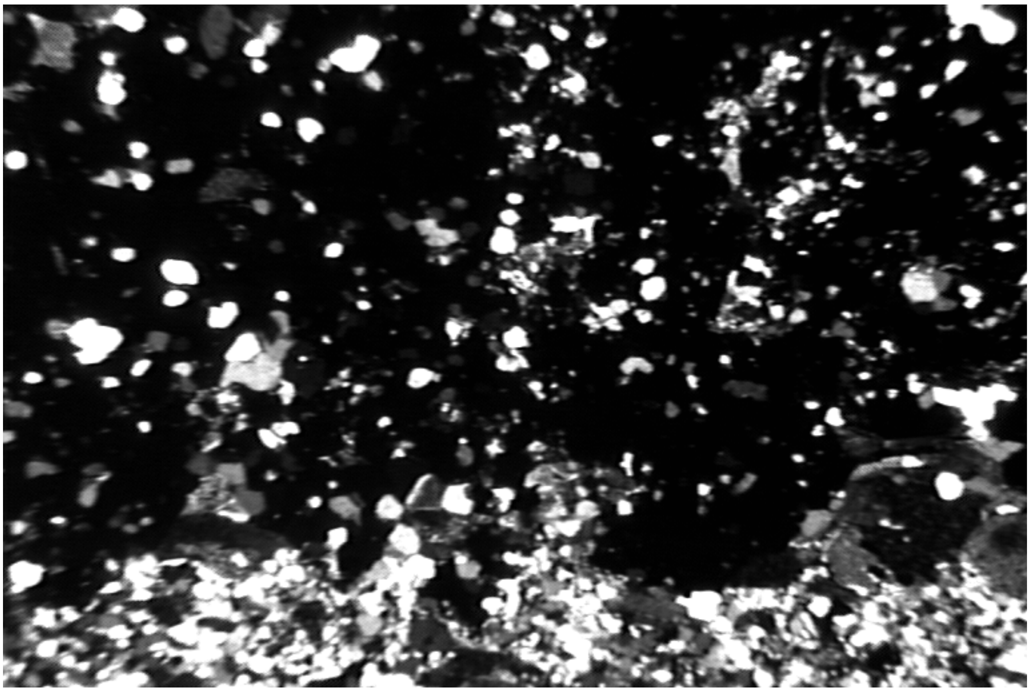
xenoblastic

porphyroblast which does not have grain boundaries controlled by its own crystallography. The two porphyroblasts below are idioblastic with respect to the matrix, but xenoblastic with respect to each other inclusion trail relic matrix grains included and then shielded by growing porhyroblast, often preserving pre-exiting foliation



poikiloblast

porphyroblast extremely rich in inclusions. The top 85% of the picture below is one grain, filled with inclusions of other minerals



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helicitic texture

inclusion trail preserving pre-existing crenulated foliation. The inclusion trail in the inclusion trail porphyroblast picture is probably helicitic.

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snowball garnet

garnet or other mineral formed in shear zone where rotation of porphyroblast during growth has resulted in spiral inclusion trail

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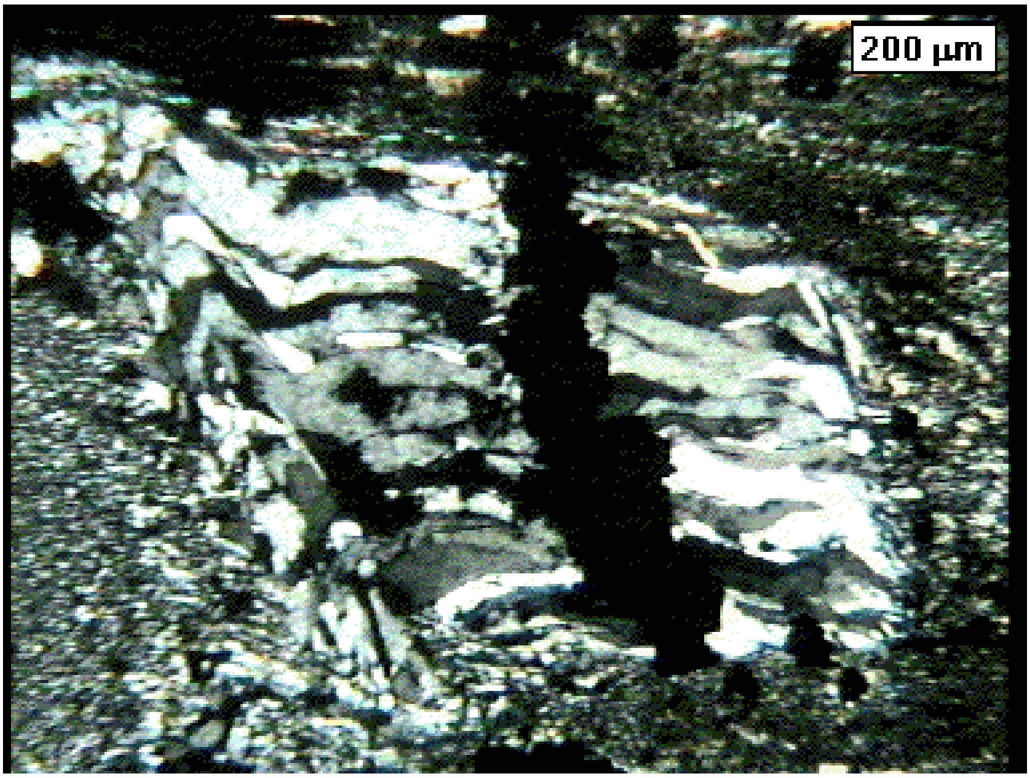
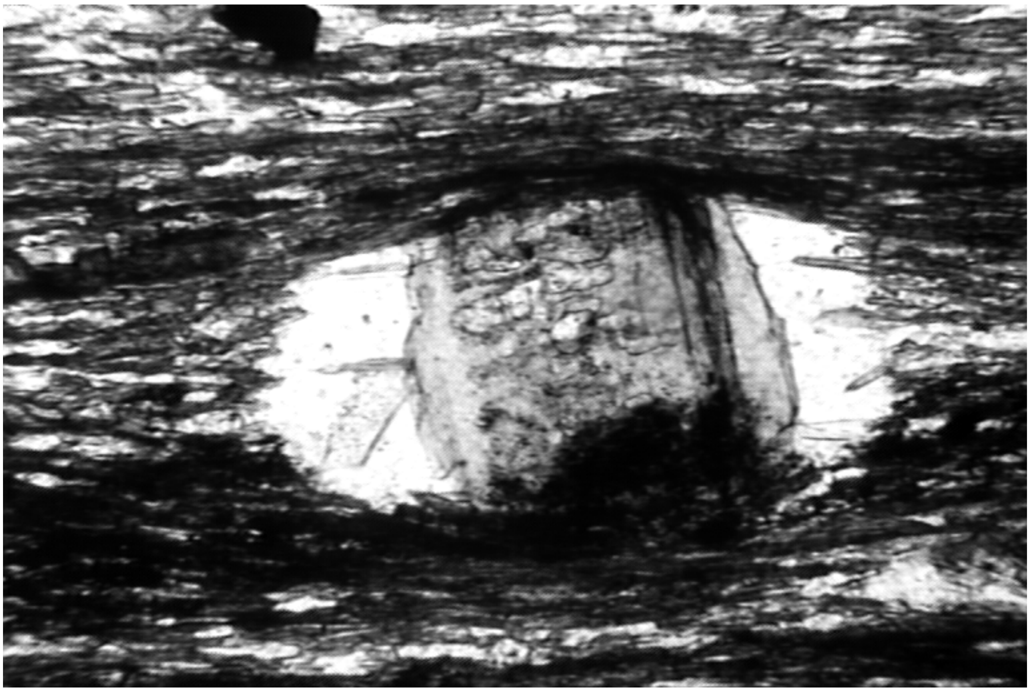
pressure fringe

areas of matrix adjacent to porphyroblast or porphyroclast in which matrix pulls away from hard mineral and a dilatent site forms which is filled with the fibrous growth of a new mineral, often quartz



pressure shadow

areas of matrix adjacent to porphyroblast or porphyroclat which are shielded by strong mineral and show equant (undeformed?) grain shapes of a mineral, often quartz. Pressure shadows could also represent recrystallised pressure fringes.

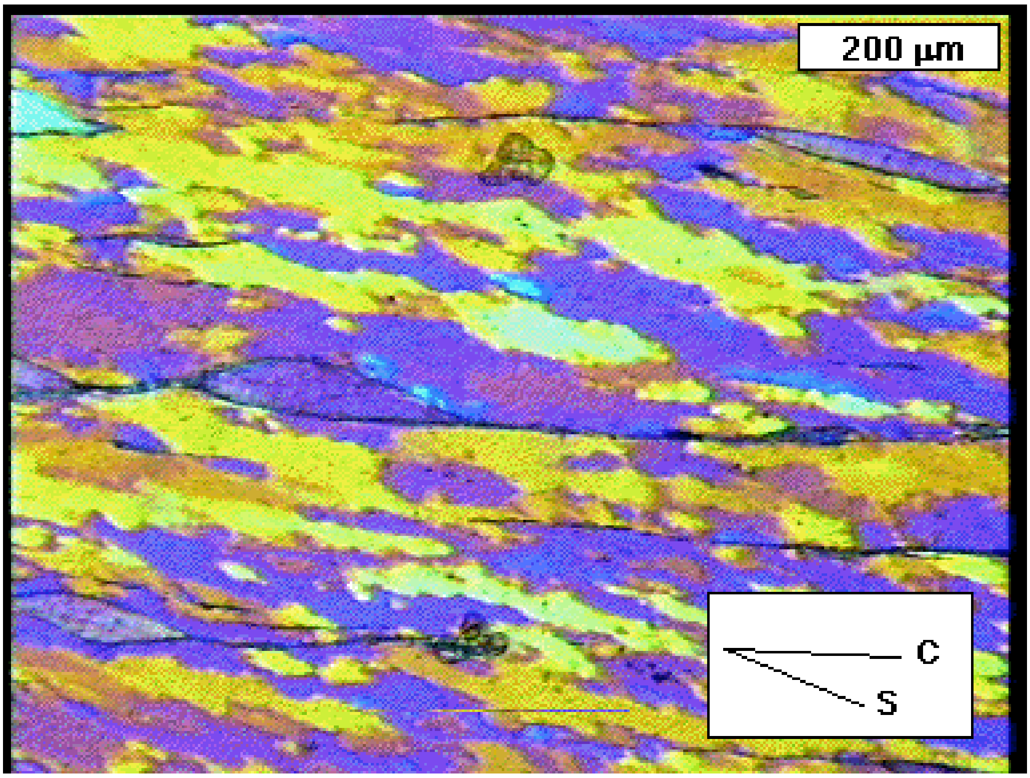


mylonite

rock which has undergone significant grain size reduction (usually as a result of a dynamic recrystallisation process). Shear zones are often made up of mylonites.

S-C mylonite - type II

S= *schistocité* = cleavage plane C= *cisaillement* = shear plane A shear zone microstructure where two foliations are present, a C plane parallel to the shear zone boundaries, often marked by mica orientations, and a cleavage plane defined by the grain shape foliation of other minerals such as quartz, which makes an angle with the C planes that decreases with increasing strain.



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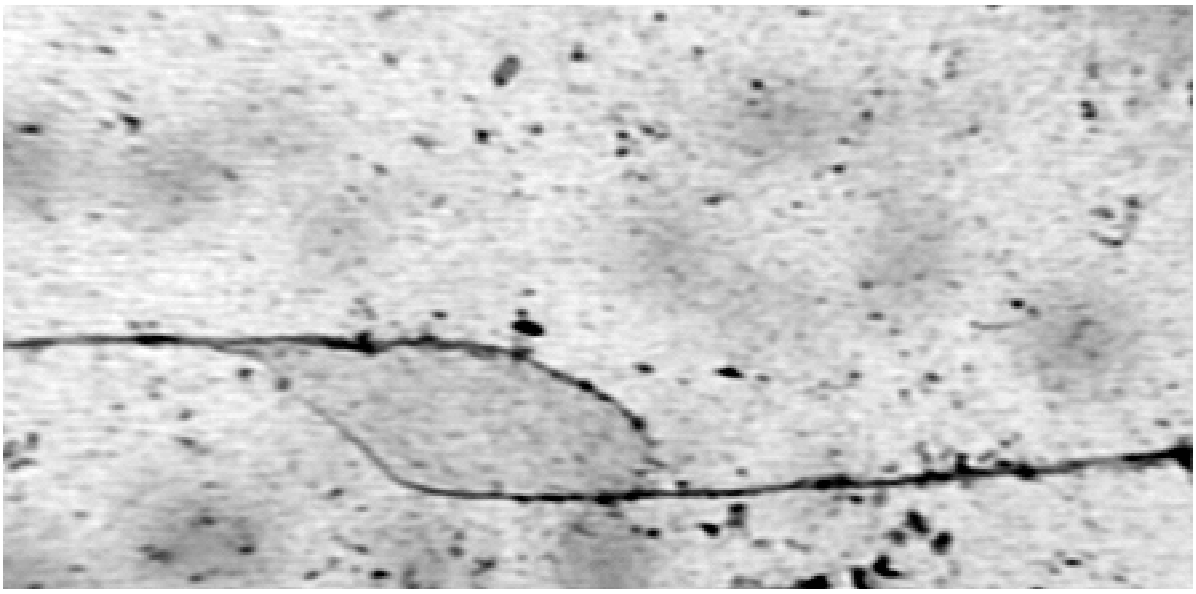
mica fish

lozenge shaped mica porphyroblasts forming an oblique foliation at an angle to the shear zone boundaries, with thin mica layers running off each end of the lozenge.



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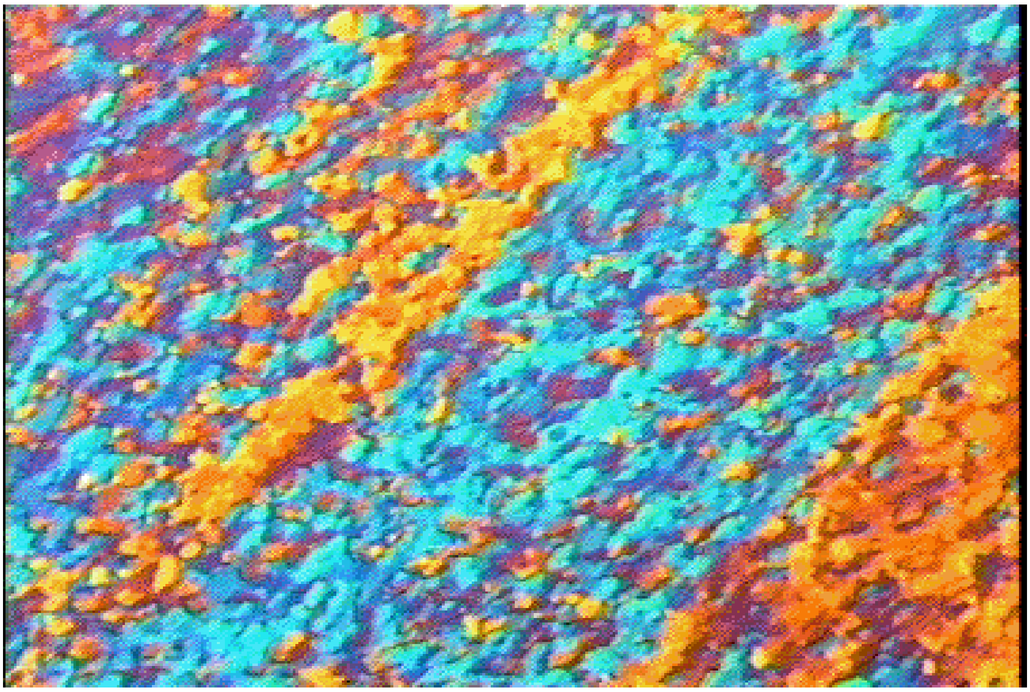
domainal fabric

microstructure distinguished by distinct domains of different character, such as different grain shape foliation orientation, or as below, different CPO. The diagonal bands in this thin section each consist of grains in with similar orientations within each band, but different orientations between bands.



Illustrated Glossary- Lecture 5

VIEPS/Mainz Microstructure Course

VIEPS Deformation Microstructures Course Lab 5 -

Fibrous (vein/fringe) - crystals in a vein or pressure fringe that have a very high length/width ratio. All fibres are parallel and the fibrous shape is not related to the crystallographic habit or lattice orientation of the mineral. Common in calcite, but can also occur in other minerals such as quartz.

Elongate-blocky - crystals in a vein that are elongate, but not as extreme as in fibrous crystals. Crystals get wider in the growth direction as some crystals 'lose' in the growth competition. Common in crack-seal veins.

See the lecture notes for other terms, such as blocky, stretched & slicken-fibres.

Syntaxial vein - Vein with one growth surface in the middle of the vein. The fibres or elongate crystals started growing at the edge of the vein and are in continuity with the wall rock.

Antitaxial vein - Vein with two growth surfaces on the edge of the vein. The vein-forming fibres are usually of another mineral than the wall rock and there is no continuity with the wall rock. Usually there is continuity of fibres on both sides of the median plane where the fibres started growing.

Composite vein - Vein with two growth surfaces. The mineral growing in the middle between the growth surfaces grows in a antitaxial manner, whereas the mineral on the outside, between the wall rock and the growth surface grows syntaxially.

Ataxial or stretched vein - Vein without a localised growth surface or where the growth surface (crack) varies in position over time.

Syntaxial fringe - Fringe with the growth surface on the outside of the fringe (between fringe and wall rock). Often mineralogical or crystallographical continuity with the rigid object causing the fringe, hence the term 'syntaxial'.

Anitaxial fringe - Fringe with the growth surface between the rigid object and the fringe. Possible continuity with the wall rock but no continuity with the object, hence the name 'antitaxial'

Displacement-controlled growth - The growth direction of fibres is determined by the opening trajectory.

Face-controlled growth - The growth direction of fibres is determined by the shape of the rigid object, with the fibres growing perpendicular to its surface.

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VIEPS/Mainz Microstructure Course

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ataxial or stretched vein

defects

cleavage

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crystallographic preferred orientation

deformation bands

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displacement-controlled growth

domainal fabric

dynamic recrystallisation

elongate-blocky

face-controlled growth

fibrous (vein/fringe)

foam texture

grain boundary migration

grain shape foliation

helicitic

idioblastic

kink bands

meta-dynamic recrystallisation

mica fish

mylonite

orientation family

poikiloblastic

porphyroblast

porphyroclast

pressure fringe

pressure shadow

ribbon grains

rotation recrystallisation

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sharp extinction

snowball garnet

static recrystallisation

subgrain

syntaxial vein / pressure fringe

twins

undulose extinction

xenoblastic

More References

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